AMERICAN

# INDUSTRIAL HYGIENE

ASSOCIATION

# QUARTERLY

VOLUME 11 MARCH, 1950 NUMBER 1

AMERICAN

# INDUSTRIAL HYGIENE

ASSOCIATION

# QUARTERLY

Volume II | MARCH, 1950 | Number I

## CONTENTS

**All papers contained in this issue were presented at the Air Pollution Institute, February 6-8, University of Michigan, School of Public Health, Ann Arbor, Michigan**



AMERICAN INDUSTRIAL HYGIENE ASSOCIATION QUARTERLY, an Official Publication of the AMERICAN INDUSTRIAL HYGIENE ASSOCIATION, published quarterly (March, June, September, December) by INDUSTRIAL MEDICINE PUBLISHING COMPANY, Chicago (publishers also of INDUSTRIAL MEDICINE and SURGERY, issued monthly). STEPHEN G. HALOS, President; A. D. CLOUD, Publisher; DORIS FLOURNOY, Editorial Assistant; HAROLD A. HOOPER, Treasurer; STEPHEN G. HALOS, Advertising and Business Manager. PUBLICATION, EDITORIAL and EXECUTIVE Offices, 605 North Michigan Avenue, Chicago 11, Illinois. Subscription $2.00 per year in the United States; $2.50 per year in Canada; $3.00 per year in other countries. Single copies 75 cents. 

Entered as second class matter May 3, 1948 at the post office at Sheboygan, Wis., under the Act of March 3, 1879.

AMERICAN
INDUSTRIAL HYGIENE
ASSOCIATION
QUARTERLY

Volume II | MARCH, 1950 | Number I

# Fundamental Methods of Atmospheric Sampling

RALPH G. SMITH,
Industrial Hygiene Chemist, Bureau of Industrial Hygiene,
Detroit Department of Health

THE general problems involved in sampling air and other gaseous mixtures for contaminants have been recognized and studied for many years by investigators concerned mainly with health conditions in working environments. Much of the literature on this subject contains information that is directly applicable to the problems encountered in air sampling for the purpose of atmospheric pollution study. Although similar in many respects, the sampling technics of industrial hygiene should be differentiated from those of atmospheric pollution. Inasmuch as the chemical and physical information sought is nearly identical in both fields, it is apparent that the differences are largely a matter of degree. Thus, atmospheric pollution study requires the sampling of very heavily contaminated air, as in stack effluent evaluations, and at the same time the sampling of air containing extremely minute amounts of contaminants, as in ordinary urban atmospheres. Many of the difficulties of such varied types of sampling have been solved in part by industrial hygiene studies, and technics may be adopted with few or no modifications. A number of unique problems remain, however, which it has been necessary for those interested in atmospheric pollution measurement to study.

In the discussion to follow, the type of information to be sought in sampling will be considered without reference to the reasons for desiring it. Much has been written on why certain data are needed, and the comment offered by Hemeon[1] is suggested as being an excellent survey of this matter.

## Particulate Matter

THE simplest type of information to be found by sampling is that concerning the total amount of particulate matter in measured amount of air. The basic problems are the efficient separation of the particulate matter in quantities sufficient for weighing, and the accurate measurement of the volume of air sampled. Stack sampling usually presents little difficulty in obtaining adequate weights, but the volume of air sampled may be quite difficult to measure accurately.

Chemical analysis of the solid matter is very often necessary. Certain sampling technics are thereby ruled out, for insufficient sample may be collected, or the collected material may be in such a form as to make analysis difficult. In general, the methods and problems of sampling for chemical analysis of solid matter are the same as sampling for simple gravimetric determinations.

One further type of information is needed concerning solid matter in air, namely, the physical characteristics of the particles comprising it. For many purposes, total weights of solids in a given volume of air are almost meaningless, and instead it is desired to know how many particles are present per unit volume. Further, the particle size distribution may also have to be known. The selection of a sampling method for the above purpose must be done with great care, for many excellent methods of solid collection themselves inflict change upon the properties to be studied. Thus large particles may be shattered into smaller ones, or the reverse may occur, and small particles are agglom-

erated. Even more serious may be the selectivity of the sampling method, such that certain particle sizes are preferentially collected while others are missed entirely. It is probably true, however, that no method of sampling now known meets all the requirements of particle size study.

## Gaseous Matter

THE collection and estimation of matter in the molecular state, i.e., gases and vapors of liquids, presents a different set of problems, and other technics must be employed. Two broad classifications of technics may be made, those suitable for high concentrations of gases, as found in stack effluents, and those suitable for the extremely low concentrations found in the atmosphere. The problem which is common to both technics is that of obtaining a volume of contaminated air for subsequent analysis, or of quantitatively trapping the desired constituents during sampling. Actual methods chosen may differ widely, as will be discussed in a later section. Often the choice of a given method will of necessity be based upon the sensitiveness of available chemical methods for determination of the contaminant.

## Measurement of Sample Volume

ALTHOUGH it is not possible in this discussion to treat the methods of measuring the volume of air or gas sampled, it must be understood that sample volume is in all instances intimately associated with both the method chosen and the expression of results. Results can never be more accurate than the precision of volume measurement. Many standard methods of metering gases are available, however, and in most instances little difficulty is encountered in finding a suitable metering device. Special problems do arise, though, principally in sampling stack effluents, where temperature may be high, corrosive gases, excessive solid matter, or water vapor are present, and air velocities may be quite low and variable. The related problem of where to obtain representative samples can only be mentioned in this discussion and is for the most part unique to each individual case.

## Methods of Obtaining the Samples

THUS far only the problems involved in sampling have been considered. The remainder of the discussion will outline methods of sampling for the various types of contaminants. The wide variety of equipment and technics available precludes any detailed considerations, and instead effort will be made to indicate significant differences between methods and the limitations which govern the ultimate choice made. Several general references are given at the end of this paper and the reader is referred to them for more detailed information.

Tables I and II present in outline form all of the traditional methods available for sampling atmospheres for their particulate matter and gaseous contaminants. Brief comment has been made of the limitations and advantages of each method.

Electric, or electrostatic precipitation, in which air is passed through a high potential electric field, is perhaps the most satisfactory method available for collecting particulate matter, as well as some mists. Collection is thought to be quantitative for all particle sizes, and a high sampling rate is possible.

TABLE I.
METHODS OF COLLECTING PARTICULATE MATTER

| Method | Advantages and Limitations |
|---|---|
| 1. Electric Precipitation | Quantitative collection, all particle sizes, may agglomerate particles. High sampling rate. Requires 110 A.C. |
| 2. Thermal Precipitation | Quantitative collection, all particle sizes, little tendency to alter particle size. Low sampling rate. |
| 3. Impingement: | |
| A. Standard impinger | Quantitative collection only down to 1 micron. May fracture large particles. Relatively high sampling rate. Heavy pump and 110 AC required. |
| B. Midget impinger | Less efficient collection, small particles, may fracture large particles. Low sampling rate. Portable and light in weight. |
| C. Impactors | Modified impingement, limited mainly to count and size studies. Excellent for sizing. |
| D. Special devices, e.g., Konimeter, Owens dust counter, B & L dust counter | For dust counting only, give empirical non-standard results, often seriously in error. Lightweight, rapid, useful for comparisons. |
| 4. Mechanical Filtration: | |
| A. Filter papers | Quantitative collection to very small sizes, simple equipment, some difficulty weighing and analyzing samples. |
| B. Paper thimbles, cloth filters, etc. | Limited use due to difficulty of recovering sample for examination. Variable efficiencies depending on design. |
| C. Chemical filters e.g., sugar, salicylic acid | High sampling rates, filter may be dissolved in solvent, danger of dirt in chemical. |

TABLE II.
METHODS OF COLLECTING GASEOUS MATTER

| Method | Advantages and Limitations |
|---|---|
| 1. High Concentrations: | |
| A. Displacement, using pipettes, bottles, etc. | Standard gas analysis methods and equipment available for most gases. High degree of accuracy. |
| B. Direct reading devices | Immediate and often continuous analysis for limited number of gases. Commercial equipment, not always portable. |
| C. Modifications of methods for low concentrations, listed below | Usually involves dilution to determinable concentrations. Only method for some gases. |
| 2. Trace Concentrations: | |
| A. Absorption in suitable media using gas washing bottles, fritted or sintered disks, impingers, U-tubes with solid absorbents, etc. | Variety of types available, often must be used in series, choice of absorbent most critical. Most widely used method. |
| B. Freeze out traps | Limited use, owing to difficulties associated with use of liquid air, dry ice, etc. Usually a "last resort method." |
| C. Adsorption, using silica gel, activated charcoal, etc. | Excellent method for most solvent vapors and other gases that will adsorb. Care necessary in properly activating adsorbent. |
| D. Direct reading instruments | Most desirable, available commercially for few gases, can give continuous readings and permanent records. Usually expensive. |

Owing to the electric charges involved, agglomeration of small particles may occur, and particle counts and size measurements will be in error for this reason. Commercially available electrostatic precipitators also require 110-volt AC current for operation, a detriment to some outdoor sampling.

Sampling by thermal precipitation, in which air passes through a field of high temperature gradient, appears to modify the size of the particles collected but little, and hence is superior to electrostatic precipitation for counting and size study. The very low sampling rate of this device, however, offsets this advantage to such an extent that it is ordinarily not used. A recent report from investigators in Los Angeles[2] appears to indicate that, in spite of the low sampling rate, this device can yield excellent samples of atmospheric dust for particle study.

The most widely used method of sampling for particle size study, and the only standardized method, is that utilizing the impinger. The sampled air is caused to pass through a small orifice and attains a very high velocity before impinging against a plate and bubbling through a liquid. Extensive study has shown that small particles are very difficult to wet and capture in a liquid, and the impinger is almost the only device that successfully accomplished this for most types of materials. Two sizes of impingers are available—the standard, which samples at a rate of one cubic foot per minute, and the midget, which samples at a rate of one-tenth cfm. The former requires a large pump and motor with a source of current, whereas the latter may be used with a light-weight hand operated pump, or a small battery operated pump. The small impinger does not retain the smaller particles as efficiently as does the large impinger, and neither device collects all particles less than a micron in diameter.

A highly specialized application of the impingement principle is embodied in the impactor type of sampling instrument. Multiple jets of decreasing orifice size are arranged in series so that air passing through them attains increasing velocity at each stage. The net effect is to modify the size distribution of particles collected at each stage, and enable particle size studies to be more accurately performed. Several modifications of this device have been described in the literature.

Other specialized uses of the impingement principle yield non-standard counts and some size data, and may be useful for localized range-finding purposes, but cannot be correlated with standard data. Air enters the sampler, where it may be expanded and humidified so that droplets form and impinge on a plate, or else the air impinges against a sticky surface and the particles are retained. Light weight, hand operation and rapid determination are the outstanding advantages of such instruments which include the konimeter, the Owens dust counter and the Bausch & Lomb dust counter.

Filtration methods of sampling, in which air is passed through high purity analytical filter papers, have been increasingly used in recent years. High efficiencies of collection and rapid sampling rates are possible, and collectors are readily made from a variety of materials. Useful data may be obtained by examination of the stains produced on the papers for certain contaminants, and samples are easily analyzed for their chemical constituents. Direct weighing of the papers is difficult, however, and particle study is hampered by difficulties encountered in removing the sample from the paper. Individual studies are usually required to determine

the type of filter paper most suitable. Paper thimbles have been used for filtering particulate matter, but have little to recommend them in place of filter papers.

Filter materials which readily dissolve in a common solvent are useful for sampling particulate matter, primarily because of their low resistance to airflow and resultant high sampling rates. Sampling rates of 30 cfm and greater are possible with only a moderately-sized salicylic acid filter, for example, and this feature is very desirable when a sufficient sample for analysis and particle study must be obtained from relatively "clean" city air. Sugar has also been used for this, but is rarely dust free to the extent that it can be used for particle counts.

The technics for sampling high concentrations of many gases have been well established for many years, and may be found in standard texts on gas analysis. They consist for the most part in withdrawing a sample of the gas mixture into a pipette, bottle, or other suitable container. Aspirator bulbs, pumps, etc., may be used for this purpose, or a liquid such as water may be displaced by the gases. Subsequent treatment of the samples involves absorption and/or combustion of the various gases in commercially available gas analysis equipment. Such methods, of course, are completely unsuitable for trace analysis work. A few direct reading devices are available for common stack effluents, but these must usually be specially installed and calibrated devices.

Although stack effluent sampling is often necessary, the bulk of the sampling required in evaluating atmospheric pollution is concerned with the outdoor air itself, where significant concentrations may be a fraction or a part per million. As indicated in Table II, most methods for sampling such low concentrations rely on absorption of the gas in a collecting medium which will dissolve or chemically combine with it. A wide variety of absorption vessels are available for such procedures, and no detailed description of their particular usages is possible in this brief presentation. It may be stated that those types of absorbers which most finely disperse the sampled air and permit the greatest distance of travel in the absorbing chemical are most satisfactory. The use of fritted or sintered glass disks provides the greatest gas dispersion of any of the absorbers, and spiral and helical type absorbers provide the maximum length of travel. Impingers may be successfully used for many types of sampling, but do not provide sufficient dispersion for complete absorption of most gases. U-tubes containing solid absorbents are often very efficient collectors owing to the high concentration of absorbent present in them.

Methods in which gases or vapors are condensed from the air by passage through a freezing trap are ordinarily used only when other methods prove unsuccessful. Inherent difficulties in handling such coolants as solid carbon dioxide and liquid air are deterrents to the use of such methods.

Certain contaminants are quantitatively adsorbed by activated materials such as charcoal and silica gel, and the use of this method is satisfactory for such materials. Frequently an interfering substance may be effectively removed by this means, too, enabling collection of the desired contaminant by some other method.

A very limited number of instruments are on the market which yield direct analyses of the air for certain contaminants. Their usefulness is apparent, particularly when continuous recorded values are obtained.

From the brief summary of basic sampling methods just presented, it can be seen that for the most part the means are at hand today for rather extensive sampling of the atmosphere. Greatly increased interest in atmospheric pollution has stimulated research and development of new methods, and it is likely that in the near future many new instruments and methods will appear. Research in this field should be largely devoted to methods which are rapid, direct reading if possible, and which are above all accurate and uniform in performance. The methods and approach described in the Los Angeles report[2] are an excellent example of the latest reported investigations.

## References

1. *Chem. & Eng. News*, 27, 3632, December 5, 1949.

2. Second Interim Report on the Smog Problem in Los Angeles County, Stanford Research Institute, Committee on Smoke and Fumes, Western Oil and Gas Association, Los Angeles, California.

3. JACOBS, M. B.: Analytical Chemistry of Industrial Poisons, Hazards and Solvents. Interscience Publishers, Inc., New York (second edition) 1949.

4. SILVERMAN, LESLIE: Industrial Air Sampling and Analyses. Chemistry and Toxicology Series; Bulletin No. 1, 1947, Industrial Hygiene Foundation, Pittsburgh.

5. BROWN, C. E., and SCHRENK, H. H.: Standard Methods for Measuring Extent of Atmospheric Pollution. Information Circular 7210, U.S. Dept. Interior, Bureau of Mines, May, 1942.

# Filtration Through Porous Materials

LESLIE SILVERMAN, Sc.D.,
Associate Professor of Industrial Hygiene,
Harvard School of Public Health,
Boston, Massachusetts

THE purpose of this discussion is to present the fundamentals, requirements, and operating characteristics of filters applied to cleaning of air and gases discharged from industrial processes. Many types of filters are now used to remove particulate material from air and gases. They are usually considered to be second in scope of application for industrial gas cleaning and are also ranked next to inertial and centrifugal collectors in capital and operating costs.

Efficiency of filtration units is variable, but in most dust and fume control installations, weight removal values well over 95% are obtained with reasonable power consumption.

Filtration is used for all types of particulate material ranging from coarse dusts for use in subsequent processes materials handling) to fine fumes. It is perhaps the most important method in use for recovery of metal fumes in the metallurgical industry. The theory of filtration and experimental results indicate that particles ranging from 0.01 microns to coarse screen sizes may be successfully filtered and collected. Filtration may also be applied to a wide range of gas and air temperatures within the mechanical and strength limits of filter media.

Filter devices are used for pre-cleaning industrial process atmospheres, air conditioning, and many special industrial applications. These uses constitute a major portion of filter installations in numbers. Their most important application in atmospheric pollution control, however, is for cleaning air and gas discharged to the ambient air. This discussion will be devoted primarily to these units with special emphasis on the widely used cloth, screen, tube or bag collector. In factory and process effluent control, many filter units are preceded by a primary cleaner.

## Factors in Porous Media Filtration

BASIC considerations in filtration may be divided into two aspects. The first is a study of filtration media characteristics and the second is devoted to a discussion of aerosol influence on filter performance.

Filtration of aerosols can be accomplished by two distinct methods. In one, the media acts as the separator and for this purpose the composition and nature of the filter are important. Such filters are applied primarily for pre-cleaning or handling light dust loads (ranging from 0.0002 to 0.01 grains per cubic foot). High efficiency units of this type may be used as after cleaners for other removal units including some filters which separate the mass concentration ($>2$ to $5\mu$ particles).

In the second type, the media acts primarily as a reasonably high efficiency filter ($>90\%$) which provides a means of building a supporting bed of aerosol particles. The major portion of the particulate matter to be separated is removed by the layer or bed formed on the media surface. This layer is periodically removed from the surface in practice. Some penetration within the interstices takes place, however, which often improves the over-all filter performance. Eventually such penetration may significantly alter the media resistance characteristics as discussed below.

A. FILTRATION MEDIA CHARACTERISTICS:

*Materials:* A wide number of materials may be used for filtration of air and gases. For high efficiency with light loadings or ultimate filtration, the media may be wool fibers, impregnated with resin, asbestos, cellulose, or glass fibers. These media can clean gases with efficiencies above 99.99%. In these materials, fiber diameter is important since it fixes the filter surface, contact and volume characteristics. Another form of this filter is the large coke or sand beds which have been used for acid mist and similar aerosols.

The common filtration medium for commercial dust and fume removal units is cloth fabric. This cloth may be woven from cotton, wool, asbestos, or synthetic materials (nylon, vinyon, glass, etc.) depending upon application factors such as gas temperature and other considerations. In

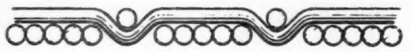


Fig. 1.
Cross section of five harness warp sateen filter cloth showing construction. Cross hatched warp thread filler threads lightly shaded. Top is face of cloth (after Weischhaus[9])

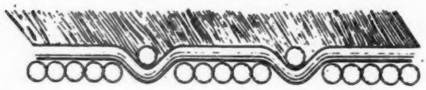


Fig. 2.
Same material as in Fig. 1 but napped to form "canton flannel." The napped surface is used for filtration. Fibrous materials may become permanently enmeshed in this surface (after Weischhaus[9])

most industrial dust collection units, cotton cloths are employed whereas for metallurgical fumes, wool bags are provided.

The cotton fabric used frequently for dust collector applications is known as a five harness warp sateen (weight approximately 12 ounces per square yard). Fabrication of this material is shown in cross section in Figs. 1 and 2. Fig. 1 indicates the thread construction and below it (Fig. 2) schematically shows the napped surface. Other media used for this are cotton or wool felt which usually give high initial filtering efficiencies.

*Resistance:* Flow through filtration media in the range usually employed for particulate collection is considered to be streamline or viscous. Under this condition resistance varies directly with air or gas flow as shown in Fig. 3. This may be expressed in simple mathematical form as:

$$R_1 = K_0 V \qquad (1)$$

where $R_1$ = resistance in inches of water.
$V$ = Filtering velocity in feet per minute (at approach to gross or face area.)
$K_0$ = Resistance coefficient—in this case denoted as cleaned cloth resistance.

Initial cloth resistance values upon installation (before any dust loading) are slightly less than cloths that have been in service and cleaned by rapping or shaking.

The filter resistance coefficient, $K_0$, of course depends on many factors such as gas or air density, viscosity and cloth or media porosity. The latter factor is dependent upon such items as thread count and fiber diameter. When filtration takes place by deposition on the fibers, resistance change depends upon porosity variation of the media. Until

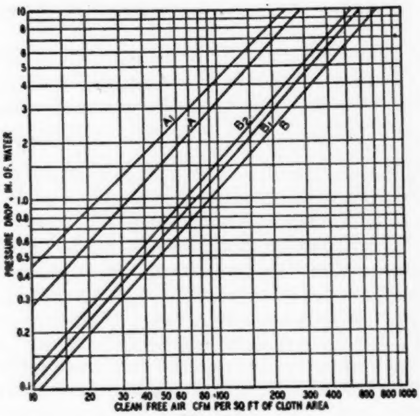



Fig. 3.
Resistance characteristics of typical sateen weave cloth. Thread count 96 x 64 (after Mumford et al[11])

Cloth Characteristics

| Curve Symbol | Cloth Weight yds. per pound | Flameproofed |
|---|---|---|
| A | 1.05 | Untreated |
| A[1] | 1.50 | Mixture of ammonium phosphate and boric acid solution |
| B | 1.30 | Untreated |
| B[1] | 1.30 | Sodium borophosphate solution |
| B | 1.30 | Sodium-ammonium-borophosphate solution |

the interstices and voids are greatly reduced in size, resistance increases linearly. If the void size decreases to the critical value then increases in resistance are exponential (n values approach 2).

*Efficiency:* The efficiency of a filtration medium such as those described above depends upon many factors because separating forces are present. Since the time of this discussion is limited, no attempt will be made to elaborate on mathematical theories of filtration. Considerable investigation of this field in the past 10 years has been stimulated by the need for efficient chemical warfare smoke filters. For an excellent and scholarly presentation of this subject the reader is referred to Davies' recent article.[1]

Forces present for separating depend principally upon the particle size of the aerosol. The theory as yet does not present an exact evaluation of each mechanism involved but the forces and size range over

which they are considered as most effective are given below.

| | Force | Particle Size Range |
|---|---|---|
| (a) | Diffusion (Brownian motion) | $< 0.01\ \mu - 0.2\ \mu$ |
| (b) | Streamline contact (fiber effect) | $> 1\ \mu$ |
| (c) | Inertia (impingement) | $> 2\ \mu$ |
| (d) | Electrostatic charge (Electrophoresis) | $> 0.01\ \mu$ |
| (e) | Sieving | > Filter pore size or pore size of deposited filter layer |

These items are discussed in detail by Davies with the exception of sieving. It is easily shown, however, that sieving has little effect on performance of the media since the pores are usually larger than any particle to be filtered. In contrast, sieving is an important mechanism in deposited layer filtration.

*Life:* Fig. 4 shows graphically the influence of fabric type on filter media life. In a simple sieve, a bed of particles is soon formed and the resistance rises rapidly as the pores are blocked. In a napped surface, particles are distributed so that more dust may be collected before flow resistance attains the same value. In a "deep bed" or fiber-maze such as felts provide, a large volume exists for storage of particles. The finer fiber sizes provide greater surface area and more contact is possible. Fig. 5 shows a felt cloth cross section under three different conditions and indicates the effect of penetration on life of this material. Felts are principally applied in reverse air-jet cleaning units which will be discussed in detail later.

B. CHARACTERISTICS OF THE AEROSOL TO BE FILTERED:

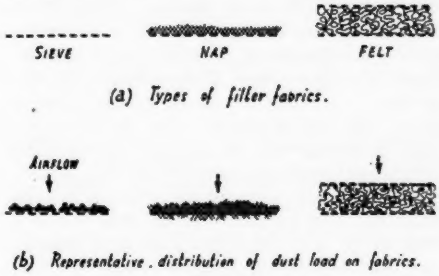



Fig. 4.
Factors influencing life of filter media. Dust distribution on various media (after Billington and Sanders[10])

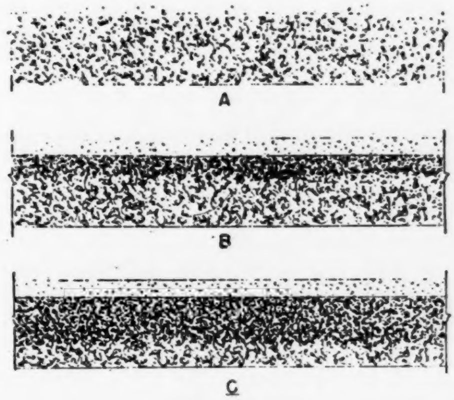



Fig. 5.
Felt filter cloth section showing effect of penetration: (A) Cake upper section as formed initially (B) Cloth in service for some time (C) Cloth after extended use indicating possible degree of pore "plugging" with resultant resistance increase (after Weischhaus[9])

The characteristics of the aerosol to be filtered are of importance in deposited layer filtration since they determine its distribution and porosity. It should be recognized that certain particle characteristics may create difficulties for removal by filtration, thus oil mists may coat the fibers and dissipate the surface charge particularly in resin wool filters. Greasy and reactive particles may pack and cling making it difficult to clean the filter whereas fibers may become enmeshed in the napped layer (Fig. 2).

The important factors which influence layer filtration are the following:

(a) Particle size.
(b) Particle shape.
(c) Specific gravity of particles.
(d) Particle surface characteristics.
(e) Packing characteristics.
(f) Amount of dust or fume on filter at end of any given period of operation.
(g) Density of gas.
(h) Viscosity of gas.

The influence of each of these factors will be apparent from the resistance discussion.

*Resistance:* The resistance to gas flow through a filter layer composed of particles has been studied by many investigators.[2,3] The most useful form is that developed by Fair and Hatch[4] from D'Arcy's formula and is expressed as follows:

$$H_1 - H_2 = H = \frac{k\,\mu}{g\,\rho}\ v\,l\,\frac{A^2}{V}\,\frac{(1-a)^2}{a^3} \quad (2)$$

where $H_f$ = loaded filter resistance, feet of fluid (air or gas)
$H_1$ = initial cloth resistance, feet of fluid
$H$ = increase in resistance due to dust load, feet of fluid
$l$ = depth of dust deposit on filter, feet
$k$ = coefficient
$g$ = acceleration due to gravity
$\mu$ = air viscosity, English units
$\rho$ = air density, pounds per cubic foot
$v$ = average filtering velocity = rate of air flow ÷ effective filter area, feet per second
$V/A$ = ratio of volume to surface area of the dust particles on the filter, feet
$a$ = porosity of the filter bed = volume of voids ÷ total or bulk volume of dust

Williams, Hatch and Greenburg[5] have modified this as follows for air filtrations:

"The depth of the filter bed, in the above equation, may be expressed in terms of the weight of dust per unit of cloth area and the density and porosity of the dust as follows:

$$l = \frac{w}{\rho^1 (1 - a)} \qquad (3)$$

where $w$ = weight of dust on the filter per unit of cloth area, pounds per square foot
$\rho^1$ = real density of the dust, pounds per cubic foot

This expression may be further modified to include the time factor by substituting for w the following:

$$w = \frac{L\ t\ v}{7000} \qquad (4)$$

where $L$ = loading of dust coming to the filter per unit of air volume, grains per cubic foot
$t$ = elapsed time of operation in seconds during which the filter resistance increased H feet

With these modifications, the complete relationship becomes:

$$H = \frac{k\mu}{g\rho}\left(\frac{A}{V}\right)^2 \frac{1-a}{a^3} \frac{v^2 L\ t}{7000\,\rho^1} \qquad (5)$$

Equation (5) gives the effects of particle size and porosity. A study of this equation shows that particle size affects resistances inversely as the square, and indicates why fine particles are harder to collect and create higher filtration resistances. Slight changes in porosity can also cause large changes in resistance as discussed in detail by Williams et al.[5]

Equation (5) can be simplified for practical consideration to the following form:

$$R_f - R_1 = K_1 V_w = \frac{K_1 L T V^2}{7000} \qquad (6)$$

where $R_f$ = final resistance, inches of water
$R_1$ = initial resistance, inches of water (see Equation (1)
$R$ = net resistance due to dust or fumes, inches of water
$K_1$ = specific resistance of the dust in inches of water per pound of dust per square foot of cloth area per foot per minute filtering velocity
$L$ = dust load in air to filter, grains per cubic foot
$T$ = time in minutes for filter resistance to increase, R inches of water
$V$ = filtering velocity, feet per minute

Equation (6) may be combined with (1) to express total flow resistance in terms of cloth and filter layer resistance or

$$R_f = K_0 V + K_1 V_w \qquad (7)$$

Several values for $K_1$ are presented in Table I. These values were obtained in laboratory studies by Williams et al[5] and show clearly the influence of particle size and shape characteristics on resistance of filter beds.

Data on actual field units obtained by Hemeon[6] are presented below for granite dust.

| | |
|---|---|
| $K_0$ (cloth tube filter) | 0.25 |
| $K_0$ (screen type filter) | 0.85 |
| $K_1$ (granite cutting) | 3.2 |

Since this $K_1$ value is not significantly different from results of Williams and his co-workers,[5] their data may be used for estimating cloth filter performance with various dusts.

Since layer filtration is principally affected by depth of dust deposit, it is obvious that dust loading will have a significant effect on resistance. The data shown in Fig. 6 are based on coarse dusts (road dust) such as those used in carburetor air cleaner tests and show quite clearly the effect of dust load on resistance of various types of cloth. Effects of sieving or layer filtration are compared to media deposition. Fig. 7 presents resistance on pressure drop data for a sateen cloth with various coal dust loadings and air volume per square foot of cloth. Resistance is considered to increase directly with time in Equation (6) in actual practice, however, this may be exponential as

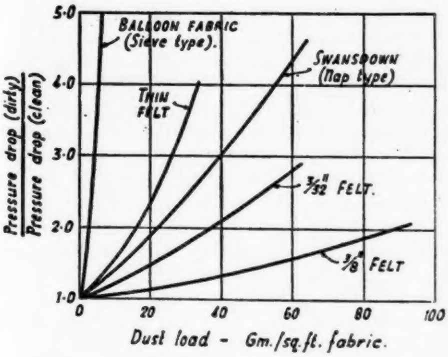



Fig. 6.
Effect of dust load on pressure drop of various fabrics (after Billington & Saunders[10])

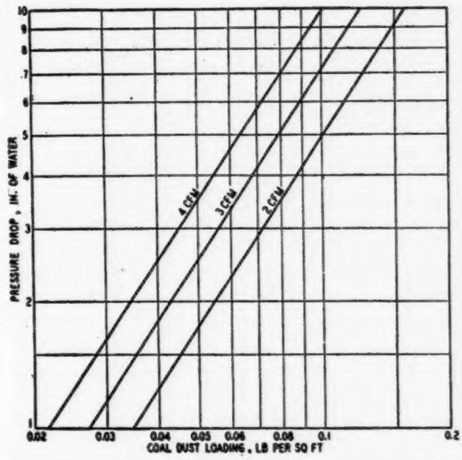



Fig. 7.
Pressure drop through cloth A[1] (Fig. 3) with various coal dust loadings and flow rates (after Mumford et al[11])

shown by Bloomfield and Dalla Valle.[7] In most filter installations, velocity also decreases as resistance increases and therefore effects of the two factors tend to balance.

*Efficiency and Life:* The efficiency of media upon which a deposited layer is accumulated for filtration depends considerably upon the layer composition. This deposit, as mentioned previously, also depends on aerosol characteristics and layer porosity. Since the principal mechanism under consideration in such filtration is sieving and inertia, efficiencies will depend considerably on the layer thickness and the resistance which is permissible with operation. Efficiency of composite filters on aerosols generated in industrial processes has been reported as high as 99.9% over a wide range of dust concentrations and materials.

The life of such filters depends considerably on the manner of cleaning. In operation, cleaning is performed with enough vibration to remove the major portion of the dust deposit and not the initial fine layer which acts as a filter aid for subsequent aerosol deposition. The life of the filter fabric and this layer depends upon the amount of abrasion or reorientation of fibers. Entrance of materials into the fibers may be induced by vibration or shaking. This gradually increases the cleaned cloth resistance. Vibration and shaking are the principal cleaning methods now in use but

TABLE 1.
FILTER RESISTANCE COEFFICIENTS $K_1$ FOR CERTAIN INDUSTRIAL DUSTS[a]*
(Industrial Cloth-type Air Filters)

| | PARTICLE SIZE | | | | | | |
|---|---|---|---|---|---|---|---|
| MATERIAL | Coarse | | | Medium[c] | | Fine[c] | |
| | <20 Mesh | <140 Mesh | <375 Mesh | <90 μ | <45 μ | <20 μ | <2 μ |
| Granite | 1.58 | 2.20 | — | — | — | 19.8 | — |
| Foundry | 0.62 | 1.58 | 3.78 | — | — | — | — |
| Gypsum | — | — | 6.30 | — | — | 18.9 | — |
| Feldspar | — | — | 6.30 | — | — | 27.3 | — |
| Stone | 0.96 | — | — | 6.30 | — | — | — |
| Lamp Black | — | — | — | — | — | — | 47.2 |
| Zinc Oxide | — | — | — | — | — | — | |
| Wood | — | — | — | 6.30 | — | — | — |
| Resin (cold) | — | 0.62 | — | — | — | 25.2 | — |
| Oats | 1.58 | — | — | 9.60 | 11.0 | — | — |
| Corn | 0.62 | — | 1.58 | 3.78 | 8.80 | — | — |

Inches, water gage, per pound dust per square foot cloth per foot per minute filtering velocity.
Flocculated material not dispersed, size actually larger.
Theoretical size of silica; no correction made for materials having other values of p[1].
*From Williams et al[5]

recently application has been made of reverse air jets which traverse the outside surface and blow through a small section of the cloth for short periods. Previous to this method, reverse air flow through the bags has been used. These methods may affect the cloth life.

### Types of Filters (Applications)

A. AIR CONDITIONING—PRE-CLEANING: Air conditioning or pre-cleaning filters are units composed of a variety of materials such as hemp, fiberglass, steel wool and other similar media. They are usually placed on frames or sheets. Their customary function is to clean light dust loads and linty materials. Such filters have been frequently misapplied to cleaning process effluents, in particular in small unit collectors. They are useful only for large particles.

B. INDUSTRIAL CLEANING (COMMERCIAL UNITS):

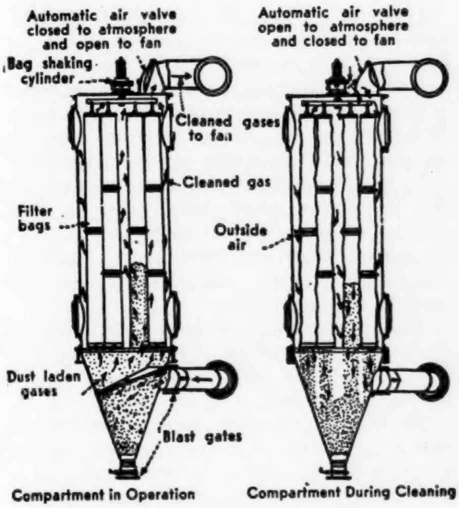
Commercial devices for industrial cleaning are manufactured on a fairly large scale and consist principally of cloth, tube, bag, or screen units employing filter cloths of the type already discussed. These collectors are available for many sources and for purposes of reference, Table II indicates the principal types and their manufacturers. Mechanisms used for cleaning include rapping or shaking units, reverse air flow or traversing air jet cleaning.

Commercial filter collectors may be placed in two groups depending upon this cleaning method. Cleaning mechanisms will affect the operating performance of the collector. A typical cloth tube unit using top shaking is shown in Fig. 8. This is a so-called automatic dust cleaning unit in which the automatic feature consists of several units of this type mounted in parallel. These are alternately removed from the exhaust system circuit during cleaning. The reverse air cleaning unit utilizes a construction similar to cloth tube models. By shutting off the power and adjusting valves, enough air flow is reversed through the bags after some shaking to collapse them and remove the dust deposit during the inoperative period.

TABLE 2.
PRINCIPAL U. S. MANUFACTURERS AND TYPES OF CLOTH FILTER DUST AND FUME COLLECTORS

| Name of Manufacturer | Address | Trade Name of Unit | Characteristics* | Method of Cleaning |
|---|---|---|---|---|
| American Wheelabrator and Equipment Co. | Mishawaka, Ind. | Dustube Dust Collectors | Vertical cloth dust tubes Standard Unit Capacities —270 to 47000 c.f.m. | Mechanical shaking at top of dust tubes |
| Blaw-Knox | Pittsburgh, Pa. | Blaw-Knox Framed Bag | Framed Bags—collection on outside of bag | Bag frames rapped by beaters vibrated by motor drive |
| Day Company | Minneapolis 13, Minn. | Autoclean Dust Filter | Vertical cloth dust tubes with traverse ring Standard Capacities — 664 to 16128 c.f.m. | Reverse air jet operating through traverse ring |
| Dracco Corporation | Cleveland 5, Ohio | Multibag Filter and Automatic Filters | Vertical cloth dust tubes Cloth areas 800 to 16000 square feet | Mechanical shaking at top of dust tubes |
| Northern Blower Company | Cleveland 2, Ohio | Norblo Standard Bag Type and Automatic Bag Type | Vertical dust tubes Standard—1872 to 33726 c.f.m. Automatic—2880 to 34560 c.f.m. | Mechanical shaking at top of dust tubes |
| Pangborn Corporation | Hagerstown, Md. | "CH" Dust Collector | Cloth covered wire mesh screen frame. Collection on outside of bag. 1080 to 29900 square feet | Mechanical rapping of frames with screen beaters |
| Pulverizing Machinery Company | Summit, New Jersey | The Mikro-Collector | Single vertical felt bag units with traverse ring. Standard sizes 500 c.f.m. up | Reverse air jet operating through traverse ring |
| Richmond Manufacturing Company | Lockport, New York | Niagara Dust Collector. Empire Dust Collector | Cloth tubes arranged in circle to revolve. Max. size 1500 sq. feet of cloth | Automatically cleaned by reverse air and rapping |
| W. W. Sly Manufacturing Company | Cleveland, Ohio | Sly Dust Filter | Cloth bags on screen frame. Dust collects on outside of bag. Capacities —1122 to 41888 c.f.m. | Bags rapped mechanically at top |
| Turner and Haws Engineering Company | W. Roxbury 23, Mass. | Aeroturn | Single and multiple vertical felt bags with traverse ring. All sizes custom built | Reverse air jet operating through traverse ring |

*Collection on inside of bag or tube unless otherwise noted.




Cross-Sectional Views of Filter Compartments.

Fig. 8.

Typical cloth tube dust collector (Dracco Automatic). This unit incorporates both mechanical shaking and reverse air for cleaning

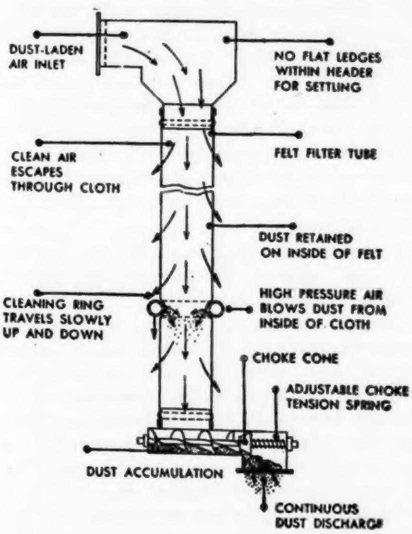



Fig. 9.

Schematic traverse ring reverse air jet dust collector (Day Company Unit)

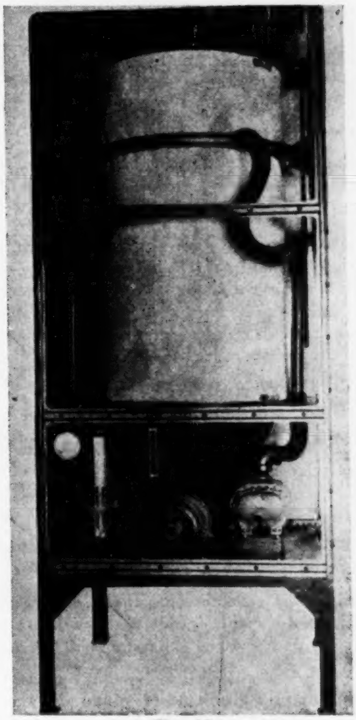


Fig. 10.

Single felt bag traverse ring reverse air jet dust collector. Hersey license (Aeroturn Unit)

The traversing reverse air jet unit utilizes a single or multiple bag with traversing rings which move up and down the bag surface. The ring is provided with an annular space through which a high velocity air jet is blown. The jet is located close to the cloth and creates flexing during the ring travel.

A schematic single bag unit of this type is shown in Fig. 9 and a photograph of a manufactured unit is shown in Fig. 10. It is claimed, and operating characteristics that we have observed verify the fact, that cloth resistance can be maintained at a nearly constant value. In usual mechanically cleaned filter bag or tube units, resistance builds up gradually to the design value or rapping cycle pressure.

An unusual type of automatic dust cleaner of the bag type developed and used in England (but not installed in this country) is the Waring Dust Collector shown schematically in Fig. 11. In this device conical bags are suspended by means of the fulcrum arrangement shown. Cleaning is automatic as the dust load builds up to a critical value on the conical bags. The pulsation

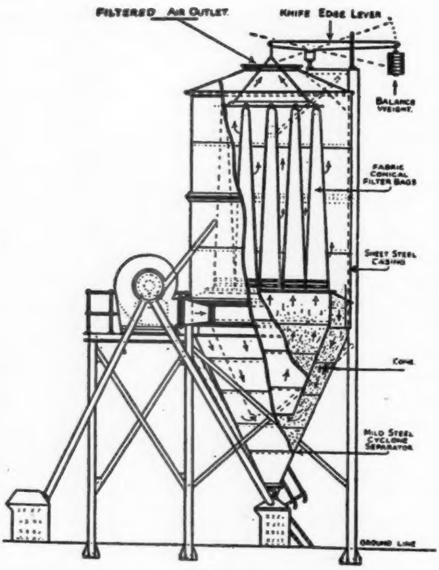



Fig. 11.
Waring dust collector (suspended conical bag unit). Note that this figure shows the combination of a cyclone separator and the filter bag collector

and vibration which take place during operation cause oscillation of the bag surface. This constantly shakes loose deposited materials. The units are reported to give satisfactory performance. This self-cleaning principle has also been applied to flat screen filters used for cleaning and recirculating air from textile mill processes. Here the deposit accumulates on an inclined filter surface. The deposited layer falls from its weight when this reaches a critical value and thereby produces self-cleaning.

### Performance

A. REQUIREMENTS: The requirements for good filter performance have been well stated by Williams, Hatch and Greenburg[5] and are given below.

1. "The efficiency of air cleaning must be high enough to meet the specifications of the particular installation with respect to the permissible dust concentration in the discharged air.

2. The resistance to air flow through the filter shall not exceed the maximum value which was used in making the original calculation for determining the size and capacity of the fan. When the filter resistance exceeds this value, the rate of air flow decreases, perhaps below the safe limit for effective dust control.

3. The maximum filter resistance shall not be developed before the end of the specified time of operation between cleaning periods, as for example, one working shift.

4. The maximum resistance allowed for in the design shall be consistent with reasonable power consumption and shall also be kept below the danger point from the standpoint of loss of filtering efficiency and good filter maintenance."

As has been discussed above, the efficiency of units of the cloth bag, tube or screen type is high and may be influenced by the material deposited.

Resistances normally used in practice do not exceed 3 inches of water but occasionally units are encountered where values of 12 inches of water give satisfactory results. When flow resistance reaches these values, power costs become excessive to maintain satisfactory controlling air volumes.

Several studies have shown that the cleaning efficiency does not vary significantly with filtering velocity *per se* inasmuch as effective results have been obtained on rock dust collection and velocities approaching 40 feet per minute. In our experience we have found that fibrous dusts originating from cotton cleaning processes may be filtered at velocities close to 150 feet per minute. High flows ordinarily only work well with fibrous materials which create porous rather than dense deposits.

B. RATING AND TESTING: The rating of filter cloth devices is determined by two values. One is the total air flow to be handled and the second is the filtration rate required for satisfactory operation. These values fix the required cloth area. The filtering velocity varies in general practice between 0.5 and 5 fpm with a common value of 3 fpm for dust collection. For fumes that flocculate and plug fabrics, the velocity is usually maintained below 0.5 fpm. These velocities are often expressed as cfm per square foot of cloth. For simple air cleaning applications such as pre-cleaning and fibrous material removal, as mentioned, velocities may exceed 100 fpm.

Another factor that is important in addition to the air to cloth ratio is the proper proportions for cloth tubes or bags. A number of experiments in metallurgical bag-

house studies have shown that as a rule the length of a bag should never be greater than 30 times its diameter. The reason for this lies in the fact that when the bag is shaken, regardless of vertical, side-wise or rotating movement, it is essential that it be flexed. A long narrow bag creates a trapping structure and the accumulated fume cannot fall properly. The empirical limit given for the relation of length to diameter represents a compromise between two desired factors. One is the maximum cloth area per square foot of floor space and the second, maximum cleaning action. If length is decreased in relation to diameter, it is clear that more bags or tubes are necessary for the same cloth area, hence more space will be required. This results in a greater number of hoppers and conveying mechanisms.

In cloth tube units with traversing jet cleaning much higher filtering velocities are used. Manufacturers (Table II) of these devices recommend air to cloth ratios (cfm per square foot) varying from 10:1 to 30:1. Because their method of cleaning is continuous and no flow interruption takes place, they can operate at nearly constant flow resistance. Mechanically shaken units increase in resistance to a definite value before shut down.

Typical cleaning cycles for the two units are shown in Figure 12. The cleaning cycle for traversing air jet units may be either pressure actuated or on a time schedule. Both types have been installed in practice although a pressure actuated mechanism for the traversing ring appears to be the method of choice.

There are certain objections to reverse flow methods of filter cleaning. The most obvious disadvantage is that complete reversing of flow may remove some of the desired filter layer. One characteristic of filters cleaned by reverse air flow is that when returned to service, dust is emitted from the collector as the layer starts to accumulate. Unless the reversing air is very clean, a layer of dust will be deposited on the outside of the filter bag. This dust can then be blown into the working space or surroundings when the unit is placed in normal operation. The reversing air should not contain moisture since it may cause a caked layer which is difficult to remove.

Temperature factors to be considered in filter rating influence choice of media. The

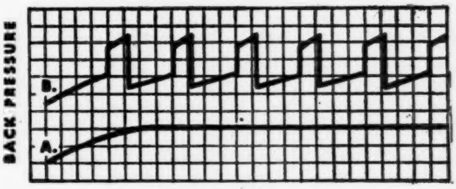



Fig. 12.

Resistance and time cycles for mechanically cleaned (automatic) and continuously cleaned (reverse air jet with traverse ring): (A) Resistance time performance for traversing air jet cleaning (B) Resistance time curve for automatic bag shaking using alternate units. Note large increase in resistance when one unit is removed for cleaning

working range suggested for cotton cloths is a maximum of 180°F, and for wool cloths, 220° F. In some instances wool may be operated at higher temperatures and camel's hair has also been used for higher temperatures than wool. Woven glass media will handle gases up to 750° F but cannot stand much abrasion from shaking. Asbestos cloths have been used but because of mechanical failure they do not give good service. Wool is more resistant to acids than cotton but not as satisfactory as glass media. At the present time, synthetic materials with various bonding agents such as silicone rubbers are under investigation and may yield better temperature resistant media. Steel wool has also been suggested as a high temperature medium.

Testing of commercial air cleaning units of the filter type may be done by several methods depending upon the application. For air pollution work, it is essential the filter remove particulate matter to meet the effluent concentration requirements established by the control authorities. This may vary from a weight value as low as 0.4 grains per cubic foot on stack discharge to plant air recirculation values less than the maximum allowable concentrations for human exposures. Testing for air conditioning system filters and similar applications is usually done by discoloration tests. Testing for recirculation conditions is done by particle numbers or weight. For materials discharged from industrial processes, the only specific American code suggested is the A.S.M.E. Power Test Code[8] for dust separating apparatus which includes cleaning

units of all types. Therefore, commercial filters may be tested by the methods outlined in this code. Fundamentally to determine the collection performance reliable aliquot samples should be obtained on each side of the cleaning unit. Performance in this respect is best stated in terms of collection efficiency and effluent concentration.

C. COST: The cost of installation of a filter bag unit depends considerably upon the size and manufacturer of the unit. Figures vary widely with different companies, and size is one of their most important criteria. For example, a 10,000 cfm unit to handle 5500 pounds of dust per eight-hour day at the present time would cost approximately 35 cents per cfm for installation. If its size were increased to 20,000 cfm handling the same amount total dust the cost would be close to 22 cents per cfm. In both cases a dust load of eight grains per cubic foot was specified. This cost includes erection and providing all the filter components such as the shaker motor. It does not include the cost of inertial separators, piping and air moving equipment. The capital cost may therefore vary, depending upon the type of unit, from 20 cents to above one dollar per cfm for automatically cleaned traverse air jet units. The higher capital cost for the latter type units is justified according to their manufacturers by the superior performance and power saving in maintaining a lower and constant resistance. The cost of bag materials for replacement varies from three to five cents per square foot.

The operating cost of a filter unit may be calculated from Equation (8) below

$$\text{Horse Power} = \frac{5.2\ Q_m R_m}{33000} \tag{8}$$

where $Q_m$ = c.f.m.

$R_m$ = over-all mean operating resistance of filter unit, inches of water

This equation states that the power consumption depends on air flow and mean resistance during the air flow period. The cost of operation can be calculated from local power rates.

D. MAINTENANCE: Maintenance and replacement of cloth bag, screen and tube dust collectors depend upon unit location (inside or outside of the plant), operation period before cleaning (frequency of cleaning), severity of acid and temperature conditions of the gas handled and nature of the aerosol (composition). Mechanical shaking and vibration result in a gradual fabric wear and eventually it must be replaced. Depending upon severity of conditions, replacement of bags or cloth may vary from 30 days to several years. Data on wear from the traversing air jet units is too meager to reach any conclusions. In two instances where we have specific knowledge their performance has been satisfactory for two years of daily (eight-hour) operation. Replacement of felt bags in these units is more costly than cotton materials.

Plant maintenance of the filter collectors is essentially a problem of preventing leaks due to holes, abrasions, seals, collars or joints that have opened. It is also essential in some instances to protect cloths from mildew or atmospheric damage and to flameproof them where sparks may be encountered. Large units are provided with walkways so that bags or tubes may be inspected at frequent intervals. Small units have inspection doors for this purpose. Part of the maintenance problem depends upon location of the unit in the plant. In many cases, collectors are located outdoors if space is a problem. Dry materials do not create serious difficulties in such locations but if wet or damp materials are handled these may freeze in northern winter climates. Such situations require the unit to be placed indoors with the effluent gas discharged outside.

## Bibliography

1. DAVIES, D. N.: Fibrous filters for dust and smoke. *Proc. 9th Int. Cong. on Ind. Med.*, September, 1948. John Wright & Sons, Ltd., Bristol, England, 1949.

2. HATCH, L. P.: Flow through granular media. *J. Applied Mechanics*, 62:A-109, 1940.

3. DALLA VALLE, J. M.: Micromeritics. Putnam Publishing Co., 2nd Edition, New York, 1948.

4. FAIR, G. M., and HATCH, L. P.: Fundamental factors governing the streamline flow of water through sand. *Trans. Am. Water Works Ass'n.*, 25, 1551, 1933.

5. WILLIAMS, C. E., HATCH, T., and GREENBURG, L.: Determination of cloth area for industrial air filters. *Heat. Piping & Air Cond.*, 12:259, 1940.

6. HEMEON, W. C. L.: Dust control in the granite industry, Part 3. *Heating & Ventilating*, 37:41, 1940.

7. BLOOMFIELD, J. J., and DALLA VALLE, J. M.: The determination and control of industrial dust. *U. S. Public Health Bull.* 217. Washington, D.C., 1935.

8. American Society of Mechanical Engineers: Test code for dust separating apparatus. Power Test Code 21, New York, 1941.

9. WEISCHHAUS, L. J.: Filter type dust collectors. *Chem. Eng.*, 54:113, 1947.

10. BILLINGTON, N. S., and SAUNDERS, D. W.: Air filtration. *J. Inst. Heat. & Vent. Eng'rs*, 15:46, 1947.

11. MUMFORD, A. R., MARKSON, A. A., and RAVERE, T.: Characteristics of cloth filters on coal-dust-air mixtures. *Trans. A.S.M.E.*, 62:271, 1940.

# Air Pollution Abatement in Chemical Plants

C. A. GOSLINE,
Consultant, Engineering Department, E. I. du Pont de Nemours & Co., Inc.,
Wilmington, Delaware

In the earlier part of this program the subjects pertained to the correction of air pollution problems. It is the purpose of this discussion to show how these phases must be integrated in order to effect air pollution abatement in chemical plants or, even in a broader sense, any type of industrial operation. The discussion is not intended to solve any particular problems, but only to clarify the issues and show the way to a straightforward approach to the problem of air pollution abatement.

Problems in air pollution abatement range from the out-and-out nuisance problems to ones of corrosion or damage; to fly ash problems; to dealings with control agencies; to sampling the atmosphere around the plants; to determining how much material is discharged from stacks; and, in general, tieing together all of the factors involved in evaluating an air pollution problem. This presentation will deal with four classifications of the subject. The purpose of the separation is to show (1) the principles involved in air pollution abatement, (2) the dispersion characteristics of atmospheric contaminants, (3) typical data required for the solution of the problem, and (4) examples of recommended methods.

## Principles of Air Pollution Abatement

The principles of air pollution abatement are threefold. The first is that a clear-cut policy must be established by top management to the effect that where pollution is known to exist, it will be abated to a satisfactory level.

The second principle of air pollution abatement is that the abatement is usually done only for public relation reasons because it usually does not result in adequate, if any, financial benefits. Industries in general have awakened to the fact that they have a community responsibility and consequently must be good neighbors. This is reflected in the tremendous amounts of money that have been spent for pollution abatement. For example, the du Pont Company alone has spent more than $15,000,000 for pollution abatement facilities. It is true that examples may be cited where the value of the product recovered has made the installation economically attractive; the return on the investment was enough to justify the installation aside from the pollution abatement reason. Mostly, however, such opportunities for recovering valuable material have already been put into use so that those which remain are economically unattractive. Hence, the only reason for installing collection equipment or some fume elimination device is to maintain good relations with the community. This latter is an asset which should not be overlooked.

The third principle is that fundamentally there are only three ways to correct a pollution problem. These are: (A) Design the process to eliminate production of the waste. (B) Install equipment to collect the wastes at the source. (C) Obtain better dispersion of the material in the atmosphere.

An example of the first item, namely, change the process, is to be found in the process for the manufacture of sulfuric acid in the chamber-type sulfuric acid plants of which there are many in operation. The exit gases from the chamber acid plant contain both $SO_2$ and $NO_2$. The latter is a particularly objectionable gas, and has an especially obnoxious appearance. The new type contact acid plants are more efficient than the chamber sets and discharge mainly sulfur dioxide. None of the dangerous nitre fumes are emitted from this operation.

An example of "B," i.e., collect at the source, can be found in many hundreds of locations, but one of the best is the installation of mechanical or electrostatic ash collectors to remove fly ash and soot from the flue gases from boiler furnaces. In this connection, it is interesting to note that for pulverized fuel firing of furnaces, the new cyclone furnace promises to greatly reduce the fly ash problem. Tests to date indicate that only about 7-15% of the ash produced by burning the coal is carried over to the stack from a cyclone furnace. If this proves true in practice, the cyclone furnace will

be an improvement, as far as pollution is concerned, over the usual dry-bottom type pulverized fuel boiler from which as much as 80-90% ash may be carried over from the furnace to the stack.

The third method is to better disperse the material in the atmosphere. This may be accomplished through higher stacks which reduce concentrations of the waste effluents at ground level. It must be recognized that higher stacks are not a cure-all, and that it is possible to increase a pollution problem by erecting a higher stack. There are formulae available for the calculation of average ground-level concentrations downwind from stacks. These formulae contain factors which have not been completely defined in the meterological sense, but which appear qualitatively correct and can be used to estimate the size of a pollution problem. The Bosanquet-Pearson data are adequate in most circumstances and have been applied by the writer with good success by taking cognizance of variations in the diffusion coefficients.

In connection with the dispersion of materials in the atmosphere, one concept of pollution abatement is that of meteorological control. This means that the plant effluents are discharged at different rates depending upon the dispersion conditions in the atmosphere. It may or may not involve forecasting of these conditions. To date, the important applications have not involved forecasting, but rather have involved measurement of actual concentrations in the atmosphere around the plant with curtailment of waste discharges whenever selected levels of contamination were exceeded. This type of operation is best exemplified by the method adopted at the Consolidated Mining and Smelting Company of Canada at Trail, British Columbia. It is immediately obvious that such a scheme is barely feasible where a group of plants are concerned or where the operation is one which requires long start-up or shut-down times.

In many plants it is manifestly impossible to adopt such a scheme simply because the plant cannot be started and stopped within the length of time that the pollution index could change from bad to good and back again. Moreover, if forecasting as such is the final criterion, it is readily apparent that the scheme does not always involve positive correction because forecasts of this nature will probably be wrong 15% of the time. Every time the plant is closed unnecessarily, lost production is incurred and, consequently, the scheme rapidly becomes unattractive. In addition, a practical difficulty in the scheme is to obtain the services of a weather engineer or private meteorological service to work intimately with the plant to effect this operation. Some few large installations have done this.

### Dispersion Characteristics of Contaminants

ALTHOUGH no two air pollutions are exactly alike, it is possible to definitely point out that the problems have certain general characteristics which must be taken into account in approaching the problem for solution. Here I intend only to outline how the manner by which the pollution is dispersed in the atmosphere will affect the problem.

As the wastes enter the free atmosphere they become entrained in eddies of various sizes. As these eddies move across the countryside, more or less mixing of the stack effluent is accomplished. The amount of mixing is dependent upon the degree of turbulence in the atmosphere. This turbulence, in turn, is largely a reflection of the microclimatic and micro-meterological conditions of that area. Certain physical conditions of the atmosphere determine the degree of turbulence. These are the vertical temperature gradient and the wind speed: Other considerations such as cloudiness, precipitation, etc., only act to modify the temperature gradient and the velocity of the wind. When the temperature decreases rapidly with an increase in height, an unstable condition is said to exist and the stack gas flow pattern is such that the smoke trail takes on a vertical and horizontal sinusoidal outline. The gases alternately descend to the ground from the stack and ascend into the air. When the temperature increases with height a stable condition, frequently called an "inversion," is said to exist. During this condition the stack gases do not disperse rapidly in the vertical plane but may spread very widely in a thin layer at or near the height of the elevation at which they were discharged. During these conditions, the smoke trails from stacks have been observed to travel great distances, sometimes as much as 20 miles, with little apparent dispersion in the vertical direc-

tion. Dispersion in the horizontal plane, however, is fairly good, but not nearly as pronounced as during the unstable conditions. The net effect is that the unstable case promotes rapid over-all dissemination of the stack gases in the atmosphere, whereas the stable condition reduces the rate of dispersion to a much slower rate.

Downwind from a stack, it is seldom, if ever, that there is contamination at a particular point present all of the time. This means that a particular point is alternately exposed to contaminated air and uncontaminated air. The available formulae give the average concentration at a point. However, the concentration at that point when the contaminant-bearing eddies are present is higher than would be indicated by the time average concentration at the same point. Moreover, within the time period that the eddy is present, there are rapid fluctuations in concentration, and within the eddy there are peak concentrations. Consequently, it is important to note that there are three concentrations of concern downwind from the stack. First, is the time average concentration at the point; second, is the average concentration within the eddy at the point when the contaminant-bearing eddy is present at that point; and third, is the absolute peak concentration of a few seconds duration that will be experienced at that point.

In general, the time average concentration relates to the damage which may be done by the fumes, say corrosion of steel work. The latter two concentrations relate to the nuisance-type of complaint though they may also be directly connected with the damage-type of problem. One way in which these data may be treated is on a probability basis.

Fig. 1 shows the results of some tests downwind from an 80-ft. stack. Temperature gradient conditions are shown in the top figure, wind speed is shown in the middle set of figures and concentration-time observations are shown in the bottom scale. As can be seen from the bottom scale, concentration varies rapidly with time. For example, in a period of two minutes concentration rose from zero to over 3 ppm and back to zero again. By taking rapid measurements of the time-concentration variations in the eddies, a comparison can be made between the average concentration

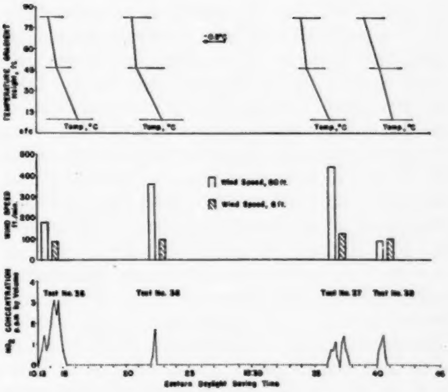


Fig. 1.
Temperature gradient, wind speed, and $NO_2$ concentration at a distance of 800 feet from stack on August 10, 1948

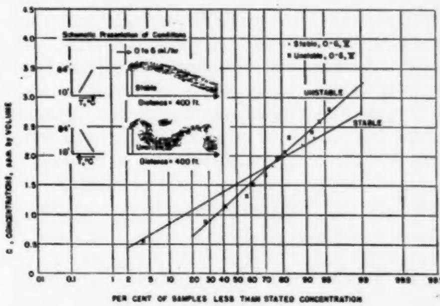


Fig. 2.
Effect of stability on concentration probability at low wind speeds and small distances

that would be experienced during different weather conditions as well as the peak concentration that might be experienced. In Fig. 2 are compared test results based on data similar to those shown in Fig. 1. Fig. 2 shows the different concentration probability (at five stack heights distance 0-6 mi./hr. wind speed at the stack top) between stable and unstable temperature gradients. It shows that 95% of the eddy concentrations will be less than $2.7^2$ $(= 7.3)$ ppm during unstable conditions and less than $2.35^2$ $(= 5.5)$ ppm for stable conditions. It is to be noted that the data for the unstable condition indicate a wider range in concentration than for the stable case. This in turn indicates a more rapid rate of dispersion because the original samples were taken in time series.

These charts have been shown to demonstrate that whereas the average concentration for periods of an hour or more may be 1 ppm, the average for one to five minutes in the eddy may be in the range of 5-10 ppm with peaks of 15-25 ppm. The absolute peak concentrations, as you will recall from Fig. 1, are of short duration and in the order of a few seconds. The duration of the individual eddies at distances up to 20 stack heights is in the order of one to five minutes. These are important when consideration is being given to the damage that can be done in any given length of time by a particular concentration of a pollutant.

Work has been reported which supports the accuracy of the Bosanquet-Pearson formula. The speaker's experience agrees with this providing proper allowance is made for the variation in the vertical and horizontal diffusion coefficients. These have been stated to average 0.05 (vertical) and 0.08 (horizontal). Hellmann, Richardson and others have observed a three-fold variation in these coefficients. Substitution of different values of p and q leads to results comparable to those developed by Sutton.

One of the common misconceptions regarding the Bosanquet-Pearson formula is the belief that it fails to fix the zone of maximum concentration at the proper distance during periods of low turbulence. That this is not so will be realized when low values of p and q (low turbulence) are substituted in the formula.

$$C_o = \frac{M}{\sqrt{2\pi}\, p\, q\, v\, x^2} e^{-\left(\frac{h}{px} + \frac{y^2}{2q^2x^2}\right)}$$

where

- $C_o$ = time average fractional volume concentration, cu. ft. of M/cu. ft. air
- M = rate of emission, cu. ft./min.
- p = vertical diffusion coefficient; average 0.05, range 0.015 to 0.15, dimensionless
- q = horizontal diffusion coefficient; average 0.08, range 0.02 to 0.24, dimensionless
- v = wind speed, ft./min.
- x = distance from stack base, ft. (along centerline downwind)
- h = effective stack height, ft.
- y = distance normal to centerline to x, ft.

For $p = 0.02$ and $q = 0.04$, the zone of maximum concentration is not at 10 stack heights but will be at 20-30 stack heights. For extremely low values of p and q, the zone of maximum concentration will be at a still greater distance. This formula lends itself to presentation on logarithmic graph paper. The use of such must be tempered with a good deal of judgment depending on the character of the effluent, the type of problem, etc.

## Data Required for Solution of Problems

ON THE basis of the foregoing, together with data about flow patterns, dispersion in the atmosphere, seasonal, daily, and even hourly variations in dispersion, etc., it is possible to develop a plan of attack on an air pollution problem. The recommended approach is as follows:

1. Determine the present or estimated levels of pollution.
2. Determine acceptable levels of pollution.
3. Determine the degree of improvement required to obtain acceptable levels.
4. Select or develop a method to accomplish the required improvement at a minimum investment and operating cost.
5. Effect the necessary installation.
6. Test to determine if requirements, equipment guarantees, etc., have been met.
7. Publish accomplishments, report results, etc., so that proper credit will be received for the abatement obtained.

In order to accomplish the first objective, it may be necessary to make a survey of the actual concentration in the atmosphere downwind from the plant. This can be accomplished by one of two general methods. The first is to install a permanent recording station to record the concentration of the contaminant, or contaminants, in question. This is fairly expensive and involves a long time to get a sufficient number of samples to provide a basis for analysis unless an elaborate network of stations can be established. The other approach is to build a mobile sampling unit that can be placed in a car or truck and transported downwind from the plant, as dictated by the vagaries of the wind direction. The latter technique has the advantage of being less expensive and permitting the acquisition of adequate data in a relatively short time during selected weather conditions with a minimum of equipment.

In making a survey of this kind it is important to obtain certain data. These are:

1. Concentration of the contaminant in the atmosphere.
2. The distance downwind from the source of pollution.
3. The elevation of the sampling point in respect to the discharge point of the pollutant.
4. The rate of emission of the contaminant from the plant.
5. The wind speed at or near the stack height.
6. Weather conditions from which it is possible to estimate the turbulence in the atmosphere, providing measurements of the vertical temperature gradiant are unavailable.

The weather conditions which should be noted are: precipitation, fog, sky cover, cloud types, and surface wind speed and temperature. From the flow patterns of the smoke, the experienced observer can accurately estimate whether the turbulence is strong or weak, or if virtually no turbulence exists.

All of the foregoing must be correlated in respect to time so that the micro-climatic influences of the area can be related to plant conditions. Any sampling scheme which fails to relate observed field conditions to the plant conditions at the time of the field measurements, fails to accomplish its purpose inasmuch as control must be effected at the plant; and, unless plant operating conditions can be related to field conditions, there is no way to accurately estimate the improvement required to reduce the pollution to a satisfactory level.

In making a survey of this type, it is also important to design the sampling in accordance with the need of the problem so that it will be possible to analyze the seriousness of the situation. For example, if the complaints are of odors that do not persist for a long time, then the sampling mechanism must be one that will incorporate a method for obtaining rapid measurements of the concentration in short periods of time. If the problem is one of corrosion or damage then a long-time average concentration may be used. Consequently, the sampling method may be one which accumulates a sample, for say an hour, and then measures the accumulated concentration in that period of time. It is, of course, obvious that the latter method smooths out all of the peak concentrations and, in light of Figs. 1 and 2, this may be a fatal error depending on the kind of problem under investigation. It is frequently difficult to develop equipment to meet these specifications and often times it is not possible to develop a sampling method exactly suited to the requirements. There is, however, a considerable amount of experience in sampling techniques and several standard types of instruments are manufactured for these purposes.

In analyzing the results for the purpose of determining the degree of improvement required, one encounters an almost complete lack of knowledge concerning normal contamination in the atmosphere in different sections of cities or the country. A number of such surveys have been made but have generally been concerned with the solids content of the atmosphere and have not been related to the normal gaseous contamination. For example, typical solid loadings in the atmosphere are tabulated below:

| | |
|---|---|
| Country | Less than 0.2 grains/1000 cu. ft. air |
| Suburban city or small town | 0.2 to 0.4 grains/1000 cu. ft. air |
| City (residential areas) | 0.4 to 0.8 grains/1000 cu. ft. air |
| Industrial sections of cities | 1.0 to 2.0 grains/1000 cu. ft. air |
| Industrial Operations | 4.0 to 80 grains/1000 cu. ft. air (7000 grains equals one pound) |

Where particulate matter is involved, another way of comparing the contamination in the atmosphere downwind from a source of pollution is to compare it with the number of particles present in the atmosphere measured in other cities. These may range from 1 to 5 or 10 million particles per cu. ft. Generally, the dust concentration is lowest in mid-afternoon and highest between midnight and sunrise. There are few if any such bases for comparison of concentrations of gases in the atmosphere.

## Examples of Recommended Methods

ONCE the degree of improvement needed in a given situation has been estimated, the various possibilities for accomplishing the indicated reduction in pollution can be considered. Recent work done on a fly ash problem at one of the du Pont plants will demonstrate the recommended procedure previously outlined.

Complaints were received from residents near the plant about the fly ash discharged from the power house. The power house includes eight boilers that produce a total of about 800,000 lb. per hour of steam. Five of the boilers are connected to one stack, three of the boilers are connected to the other stack. The boilers connected to each stack carry approximately half of the plant steam load. On the basis of the amount of steam produced, the amount of coal burned, the fraction of ash in the coal and the carryover of ashes from the furnace to the stack, it was estimated that four to five tons an hour of ashes were being discharged from the plant. Measurements were made of the discharge rate from the stacks in order to confirm these figures, and it was found that the discharge rate was five tons per hour. A survey was then made of the conditions downwind from the power house. Measurements were made of the deposition rate of dust on greased glass plates and of the concentration of dust in the atmosphere.

During normal plant operation, it was found that the concentration of suspended dust downwind from the plant was about $14.9 \times 10^5$ particles per cu. ft. of air corresponding to a weight of 5½ grains/1000 cu. ft. Within the smoke trail deposition rate of dust was found to be 93 particles per sq. cm. per minute. Samples collected from the stack were used to determine the particle size distribution of the fly ash. It was found that the ash was very fine, some 30-40% less than 10 microns in diameter, and 90% less than 80 microns in diameter.

After consideration of the dust loadings in the atmosphere downwind from the plant, it was decided that about a 10-fold improvement was needed to reduce the contamination downwind from the plant to a level normally found in residential areas in cities. This improvement meant that removal of approximately 90% of the ash from the power house stack gases was required. On the basis of the ash size distribution, efficiency curves of various kinds of equipment and costs, a multitube cyclone fly ash collectors were selected. These collectors were installed on all eight boilers at a cost of about $350,000. Tests on two individual collectors were performed to determine if they met their guarantee. The test results showed that about 85% of the ash entering the collector was being removed from the collector. Based on the size distribution of fly ash encountered at the inlet to the collector at the time of the tests, this was as good as was guaranteed. The atmosphere was re-surveyed after the collectors were installed and it was found that the particle deposition rate within the smoke trail was now 13.7 particles per sq. cm. per minute as compared to 93 while the suspended concentration was now $2.7 \times 10^5$ particles per cu. ft. of air as compared to $14.9 \times 10^5$. These deposition rates and concentration figures represent approximately 85% and 82% improvement. That is, the present deposition rate of the particles is 15% of what it was before the fly ash collectors were installed, while the concentration downwind from the plant power house is 18% of the concentration prior to the installation of the ash collectors.

It is important to note that this is in good agreement with the theory for predicting the performance of a stack. According to all of the theory, concentration downwind from a stack is directly dependent on the rate of emission of the material from the stack, not the concentration in the stack. Since 85% of the ash going to the stack was removed by the collectors, the present emission rate is approximately 15% of that prior to the installation of ash collectors. Tests show that the improvement downwind from the plant has been such that the particle deposition rate is now 15% of that prior to the installation of the collector, while the concentration of the suspended dust is 18% of that prior to the installation of the collector.

This study exemplifies all of the seven stages previously outlined. These are again:

1. Determine level of pollution—atmospheric samples.
2. Determine acceptable level—"normal" in city residential areas.
3. Determine degree of improvement—ratio $\frac{\text{actual}}{\text{acceptable}}$
4. Select method—stack samples, size distribution, gas flow efficiency curves—multitube collectors.
5. Effect installation — collectors purchased and installed for $350,000.
6. Test to determine acceptability — equipment performance tests, repeat field tests.
7. Publish accomplishments—in process by the plant.

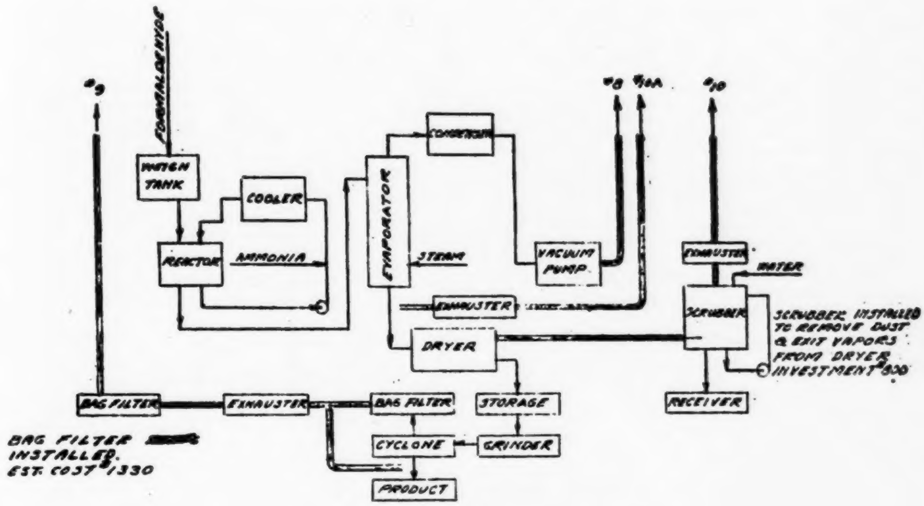



Fig. 3.
Hexamethylenetetramine flow diagram

Since each problem is different, the recovery, disposal or treatment scheme for the same gas may vary widely. These variations depend on the amount of material to be disposed, market value of recovered product, local plant conditions, etc. For example, in one department $H_2S$ is recovered or disposed of in five ways. It is:

1. Discharged through a stack.
2. Burned in a flare.
3. Scrubbed with water.
4. Scrubbed with alkali to form sodium hydro-sulfide (NaHS) or sodium sulfide, $Na_2S$.
5. Burned to form $SO_2$ and fed to sulfuric acid plant ($2H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O$).

Items 4 and 5 are performed alternately depending on the market for the sulfides. Sometimes, the $H_2S$ may be reduced to recover elemental sulfur at an unamortized cost \$0.002 to \$0.003/lb., but this is only attractive when upwards of 25 tons/day sulfur can be recovered.

A different type of work involves contacts with control agencies. In cooperating with the control agencies, it must be borne in mind that certain information about the plant is necessary to proper evaluation of the pollution problem. These data are:

1. List of materials discharged.
2. Rate of emission of materials.
3. Height of discharge points.
4. Location of discharge points.
5. Brief description of wastes and recovery, treatment, or disposal facilities.
6. Block diagram flow sheets showing waste sources and recovery, treatment, or disposal facilities.

Data such as the above plus additional information have been requested of the du Pont Company and were supplied to representatives of the New Jersey State Board of Health. Examples of this type of presentation are shown in Figs. 3 and 4. These show the sources of wastes and the method by which the wastes are treated. The numbers refer to a plan view of the plant and serve to cross-index the flow diagrams to the plan view. On the plant map are plotted the stack heights by color coding according to selected stack height ranges, say less than 50 ft., 51-75 ft., 76-100 ft., etc. In addition, the following type description may be furnished:

Stack No. 8—Bldg. No. 7—Hexamine vacuum pumps.
  Vent height—72 ft. above grade.
  Vent diameter—4 in.
  Capacity—20,000 cu. ft./hr.
  Material discharged—$NH_3$—0-10 lb./hr.

Stack No. 9—Bldg. No. 7—Hexamine.
  Vent height—72 ft.
  Vent diameter—15 in.
  Capacity—120,000 cu. ft./hr.

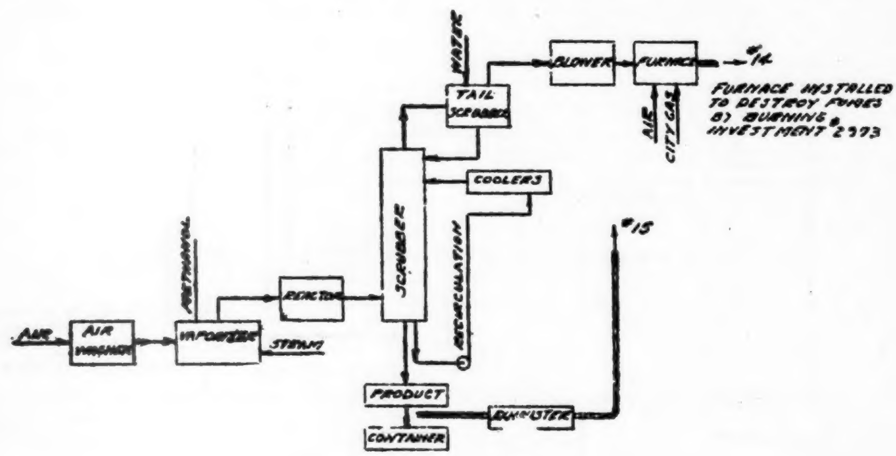



Fig. 4.
U.S.P. formaldehyde flow diagram

Material discharged—Hexamine—2 lb./hr. (estimated after bag collector).

Stack No. 10A—Bldg. No. 7—Hexamine Evaporator Hood.

Vent height—73 ft.

Vent diameter—16 in.

Capacity—180,000 cu. ft./hr.

Material discharged — Hexamine — 0.5 lb./hr.; $H_2O$—0.5 lb./hr.

Stack No. 10—Bldg. No. 7—Hexamine Dryer Scrubber Vent.

Vent height—70 ft.

Vent diameter—10 in. x 10 in.

Capacity—12,000 cu. ft./hr.

Material discharged—Hexamine vapor—2-5 lb./hr.; $NH_3$-0-1.0 lb./hr.

In Fig. 4 it will be noted that the scrubber exhaust gases are burned. This was done primarily to rid the system of high strength hydrogen off-gases which may have involved an explosion hazard (Stack No. 14). Stack No. 15 is a tank car loading vent.

The foregoing description and data represent all of the plant data that are necessary for an evaluation of the pollution problem of a plant or process. Such data as material balances, by-products produced, side reactions, product reaction rates and cycles, cost analyses, etc., are of such a nature that they can contribute little to the pollution evaluation. Since these latter may seriously reduce a company's ability to maintain its position in the highly competitive business world, and especially in the keenly competitive chemical industry, their release to the control agency is usually not required, desirable, nor for that matter requested.

Another principle of pollution abatement work is to use the most economic system to achieve the necessary reduction in discharges to the atmosphere. This may be illustrated by Fig. 5, an example of acid fume recovery. The system described does not purport to be an unexcelled absorption system; nor does the scheme imply that other systems would not be equally or more efficient. The equipment used in this case was simply the most economic to do the necessary job. At one of the company's plants, the off-gases from a chemical reaction include oxides of nitrogen and droplets of nitric acid. A portion of these are recovered in an acid recovery tower the size of which was determined after experimentation and evaluation of the economic optimum recovery rate. This disclosed that the recovery rate decreased sharply as recovered acid strength increased. The economic optimum acid strength (at this location) was found to be 45% $HNO_3$. Accordingly, this tower was installed to recover acid. It was found, however, that the gases discharged from the acid recovery tower occasionally caused a nuisance at the plant. On the basis of the distances, amounts of material, etc., discharged, it was determined that about a 50% reduction would abate the occasional nuisance at the plant. Because of consolida-

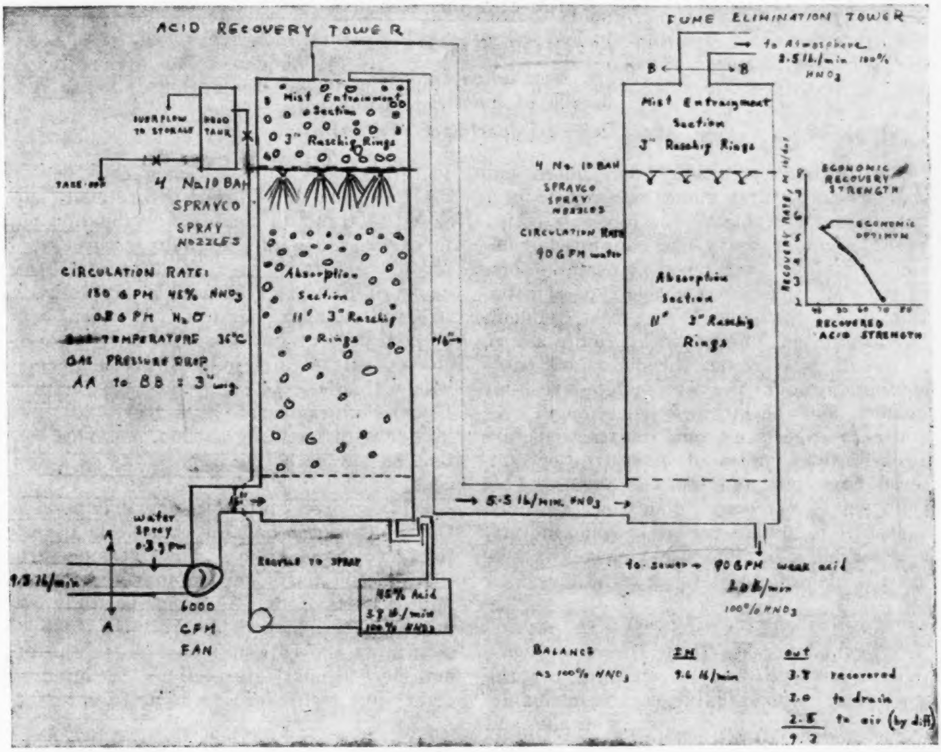



Fig. 5.

tion of production facilities, an unused tower like the acid recovery tower was available.

This tower was installed solely to further reduce the fume discharges and accomplished about a 60% reduction in the amount of nitre gases discharged.

## Summary

THE principles of pollution abatement are: (1) establish policy at management level; (2) acknowledge that abatement is usually justified as part of community responsibility; (3) recognize the three fundamental ways to pollution abatement: (a) design process to eliminate wastes; (b) collect or treat wastes at source; (c) better disperse the wastes in the atmosphere.

The characteristics of pollution dispersion in the atmosphere are such that there are three concentrations of concern. These are: (1) time average at a point—hours; (2) average during pollution presence at a point—minutes; (3) absolute peak at a point—seconds.

Steps to solution of pollution problem are seven-fold: (1) determine the present or estimated levels of pollution; (2) determine acceptable levels of pollution; (3) determine degree of improvement required; (4) select abatement or treatment method; (5) effect the installation; (6) test to determine results; (7) publish accomplishments to get credit due.

Examples show: (1) use of recommended steps; (2) contacts with control agencies and type of data that can be presented; (3) ways to handle one gas may vary due to local circumstances; (4) equipment should be designed to do only necessary job.

# Truck and Bus Exhaust

GEORGE M. HAMA,
Ventilation Engineer,
Bureau of Industrial Hygiene,
Detroit Department of Health

ATMOSPHERIC pollution from buses and trucks at first glance appears to be a rather minor problem—possibly only of importance under heavy and congested traffic conditions. However, when we examine some of our daily exposures to this type of pollution, it is probably one of the most frequently encountered. The sickening fumes associ ated with bus riding, the obnoxious odors coming through the automobile fresh-air heaters, and the burning sensation in eyes and nose at certain traffic intersections, are all typical examples of exposures encountered from bus and truck exhausts. This pollution is extremely obnoxious and disagreeable to human senses. In some individuals a feeling of illness and nausea is produced which may last for several hours.

## Composition of Exhaust Gases

THE exhaust gases from Diesel and gasoline-powered vehicles contain, for the most part, carbon dioxide, carbon monoxide, hydrogen, nitrogen, oxygen, methane and water vapor. Additional products of combustion found in very small quantities are oxides of nitrogen, aldehydes, sulfur compounds, lead compounds and some particulate matter.

From the air pollution standpoint, the most important materials in exhaust gases are carbon monoxide, aldehydes and possibly sulfur compounds. Oxides of nitrogen and lead compounds, although quite toxic, are diluted quickly in the outdoor air and are not disagreeable to human senses in minute quantities.

## Carbon Monoxide Exposures

CARBON monoxide is given off in varying quantities by Diesel and gasoline-powered vehicles. (Diesel engines under proper operating condition give off only small traces of carbon monoxide.) As shown by the curves in Fig. 1, the quantity of carbon monoxide and other gases given off is a function of the air:fuel ratio.[1] At rich idling mixtures, the air:fuel ratio may run as low as 10:1 resulting in 12% carbon monoxide in the exhaust gases. A chemically perfect air:fuel ratio of 14.7:1 is theoretically supposed to result in complete combustion and no carbon monoxide. Actually a zero carbon monoxide content is difficult to attain because of imperfect mixing of air and fuel in multicylinder engines. At open road speeds, present day gasoline-powered vehicles operate at air:fuel ratios considerably leaner than the 14.7:1 theoretical mixture. Diesel engines operate at mixtures 20:1 and higher with resulting carbon monoxide content as low as a few hundredths of a percent.

On busy street intersections, it is possible for the carbon monoxide content in the air to exceed the maximum allowable concentration of 100 parts carbon monoxide per a million parts of air. An intensive study was made by the City of Detroit[2] in 1936 to determine the carbon monoxide in the atmosphere at busy intersections. Six hundred eighty-five tests were made at 32 intersec-

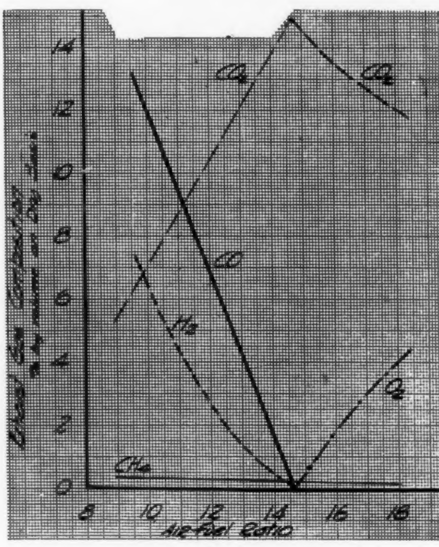



Fig. 1.
Calculated relationship between exhaust gas composition and air-fuel ratio

tions. Determinations were made at breathing levels in the street and at the curb. Wind velocity, number of vehicles passing per hour and weather conditions all appear to have some bearing on the results. The concentrations varied from zero to 310 parts per million. The average value was 100 parts per million. Inasmuch as the 100 parts per million maximum allowable concentration is based on an 8-hour exposure, it appears that the brief exposure the average citizen receives on a busy intersection will not cause him undue discomfort or ill health. Certain individuals such as traffic officers, newsvenders, door men, street cleaners, and construction workers may be exposed to excessive carbon monoxide concentrations in their daily work.

### Trend to Lower Carbon Monoxide

THE carbon monoxide concentration on street intersections has probably not increased greatly since the 1936 survey, despite the larger number of motor vehicles now in operation. Efficiency in motor design with a trend to leaner air:fuel ratios has decreased the quantity of carbon monoxide in the exhaust gases. The curves in Fig. 2 give an indication of comparative air:fuel ratios for 1927, 1933, and 1940 vehicles. These curves show a trend to leaner air:fuel

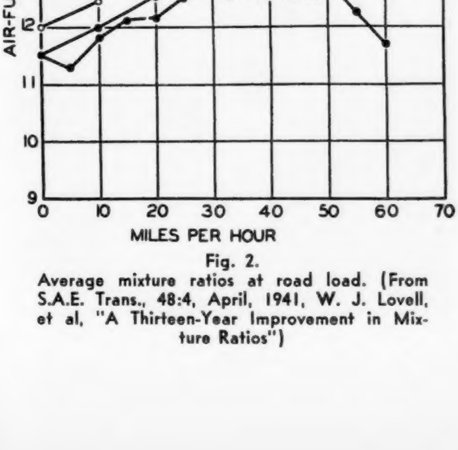



Fig. 2.
Average mixture ratios at road load. (From S.A.E. Trans., 48:4, April, 1941, W. J. Lovell, et al, "A Thirteen-Year Improvement in Mixture Ratios")

ratios amounting to an average of 2 ratios. As shown in Fig. 1, the concentration of carbon monoxide varies inversely as the air:fuel ratio. An increase in air:fuel mixtures from 12:1 to 14:1 results in a theoretical decrease in carbon monoxide from 6.5% to 1.5%.

### Sulfur Compounds

SULFUR compounds have not been completely investigated. Tests by the Detroit Department of Health indicate their presence in Diesel-engine exhaust. For the concentrations present, there is some indication that these substances are irritating. However, sulfur compounds can be maintained at a low level if the sulfur content of the engine fuel contains less than 0.3% sulfur.

### Aldehydes

DIESEL ENGINES: It is well known that Diesel-powered vehicles emit acrid disagreeable exhaust gases. Extensive tests by U. S. Bureau of Mines[4] on exhaust gases from Diesel engines, indicate that aldehydes are present and are probably responsible for the offensive character of the exhaust gas. Concentrations up to 30 parts per million have been found. It is thought that aldehydes are intermediate oxidation products resulting from incomplete combustion in lean air:fuel mixtures.

Dark smoke is sometimes given off by Diesel engines. This is associated with an improperly operated engine. Imperfect functioning injection valves, overload conditions, and other factors may produce dark smoke. Under normal operating conditions and proper fuel:air mixtures, very little smoke is present in Diesel exhaust.

GASOLINE ENGINES: Exhaust gases from gasoline-powered bus engines under certain conditions have an acrid disagreeable odor similar to Diesel-engine exhaust. Field observations have shown that this odor is present during deceleration with closed throttle and clutch engaged; i.e., when the momentum of the bus drives the engine. With these deceleration conditions, a lean air:fuel ratio results and combustion proceeds with difficulty.

Fig. 3 indicates the effect of air:fuel ratio on aldehydes. Normal gasoline-engine exhaust has a heavy sweet odor not too objectionable; lean deceleration exhaust has a

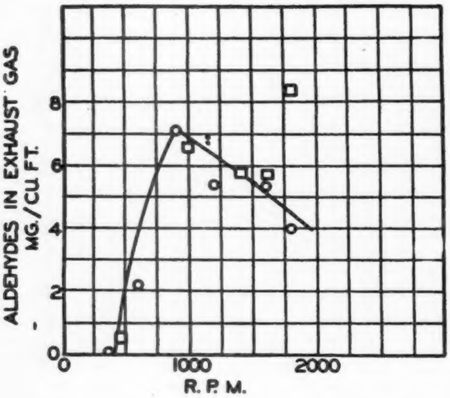



Fig. 3.
Effect of decelerating speed on aldehydes in exhaust gas (bus engine). (From S.A.E. Trans., 51:1, January, 1943, J. J. Mikita, et al, "Gasoline Engine Exhaust Odors")

pungent odor extremely irritating to the eyes, nose, throat and upper respiratory tract. Tests by the Texas Company[5] have shown that this pungent and disagreeable exhaust contains aldehydes in appreciable quantity. Aldehydes increase rapidly with deceleration speed up to about 1000 r.p.m. An increase in speed above 1000 r.p.m. slightly decreases the aldehyde content. Other substances found in the exhaust gases are lower fatty acids, oxides of nitrogen, and incompletely burned fuel; these substances, however, do not impart the disagreeable odor present under deceleration conditions. Chemical analyses of deceleration exhaust gases[5] have shown that formaldehyde is always present, acetaldehyde rarely, and acrolein never. The formaldehyde content appears to be a good index of the irritant properties of the exhaust gases.

## Odor-Control Measures

ENGINE ADJUSTMENTS: Inasmuch as the most objectionable materials in the exhaust gas are aldehydes, the control measures for odors from buses and trucks should be directed to this material.

On Diesel-powered vehicles, the aldehydes appear to be the result of lean air:fuel ratios which are inherent characteristics of Diesel engine operation and are, therefore, difficult to eliminate by engine adjustment.

On gasoline-powered vehicles, certain engine adjustments will improve but will not completely eliminate the deceleration odors. Poor manifolding may result in excessive aldehyde formation. In this case, a simple expedient is to use a more volatile fuel. Another method is to raise the intake mixture temperature or install higher temperature manifolds. Cleaning the deposits in the manifolds may reduce the aldehydes by eliminating the material that traps fuel during wet mixture conditions. Adjusting the idling mixture to the leanest possible limit also reduces the aldehydes.

CONDITIONING EQUIPMENT: The removal of aldehydes from exhaust gases by means of water scrubbing devices presents an efficient method which, apparently has not been tried on buses and trucks.

Aldehydes are readily soluble in water. If the exhaust gases can be broken up and intimately mixed with water, the aldehydes can be almost completely removed. Scrubbing devices for this purpose are now available on the market and have been used on Diesel-powered equipment for underground mining. The accompanying illustrations, Figs. 4 and 5, present scrubbers on mining Diesel engines. These scrubbers consist of a water tank into which the exhaust gases are discharged through a perforated tube. The holes break up the gases which bubble through the water. The upper section may contain plates or packed material for further contacting the gases and removing entrained droplets. This is sometimes followed

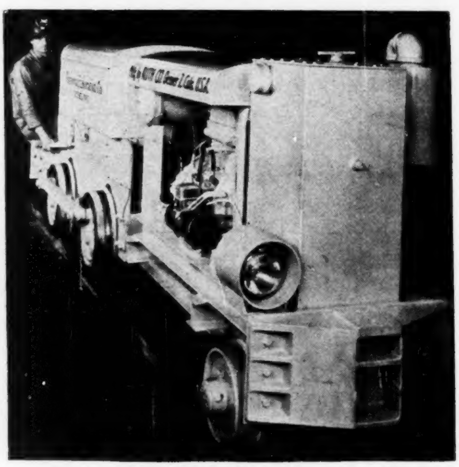


Fig. 4.

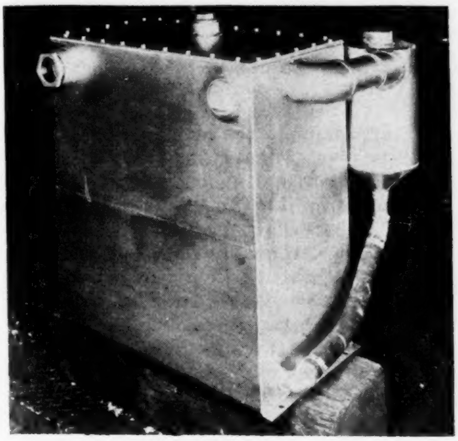


Fig. 5.

by a centrifugal-type separator. There is a slight power loss in the scrubber which has a back-pressure amounting to 1½ in. to 3 in. of mercury. Although a maximum allowable concentration of 10 parts per million parts air has been suggested, concentrations much below this have been found to be offensive. Tests by the Detroit Department of Health indicate that concentrations of 0.1 p.p.m. and lower in exhaust gases are offensive and irritating to some individuals. If the public demands the control of these obnoxious gases, it appears from tests made that scrubbers can be utilized to reduce the aldehydes below offensive levels.

## Citations

1. Personal Correspondence, Ethyl Corporation, Detroit, Michigan.
2. Unpublished Data, Paul Klebba, M.D., Detroit Street Railways, City of Detroit.
3. LOVELL, W. J., et al: A Thirteen-Year Improvement in Mixture Ratios. S.A.E. Trans. 48:4 (April) 1941.
4. U. S. Bureau of Mines, Report of Investigations 3508. Diesel Engines Underground.
5. MIKITA, J. J., et al: Gasoline Engine Exhaust Odors. S.A.E. Trans., 51:1 (Jan.) 1943.
6. The Ruth Company, Denver 2, Colorado.

# Metallurgical Furnace Stacks

C. A. BISHOP,
Research Associate, Carnegie-Illinois Steel Corporation,
Pittsburgh

IN THE metallurgical industries one finds a large variety of chemical reactions and physical processings being carried out at high temperatures. The attainment of these temperatures means in general that something is being burned. Whether that something is a part of the material in process, or is one of many different fuels, the same problem exists to a greater or lesser extent in all but a very few of these combustion processes, namely, air pollution.

As you are well aware, the abatement of such pollution has been the object of a considerable amount of attention in recent years, particularly in those areas where a heavy concentration of industry may combine with local meteorological conditions in such a way as to accentuate what might otherwise be harmless atmospheric contamination. In the smaller community, where the answer to the pollution problem is relatively simple, the voluntary assumption of their respective responsibilities by the industry and citizenry concerned may be sufficient to bring about the desired improvement. Even as communities go up in size and the problems become more complex, unified corrective action can best be effected by collaboration among all interested parties.

When one considers the size and the variety of the operations conducted in these larger communities, the magnitude and complexity of the job to be done can be readily visualized.

For example, the steel industry in the United States, as recently stated by the magazine, *Steel Facts,* covers a total area of approximately 74 square miles. This is somewhat larger than the District of Columbia. This composite plant would contain 246 blast furnaces, 1,210 steel-making furnaces, and approximately 15,000 coke ovens in addition to the rolling mills, and other manufacturing and shipping facilities involved in the process of producing the country's steel. The mills and furnaces of the industry are now spread over 30 states with more than 400 plants, making or finishing steel in 250 communities.

To approximate the amount of fuel used by these plants, figures have been prepared showing that the industry's possible requirements for fuel in a year are over one billion gallons of fuel oil, several hundred billion cubic feet of natural gas, 17 million tons of coal burned in boiler houses, and 94 million tons of coal required to supply coke for blast furnaces.

The problems facing an industry burning this amount of fuel are numerous. To highlight the progress that has been made, the scope of this paper will be limited for the most part to a discussion of the problems associated with pollution abatement in the steel industry located in Allegheny County, Pennsylvania. The selection of the work being done in Allegheny County to serve as an example of the general problems of the entire industry is appropriate since about one-seventh of all the nation's steel capacity is located there.

The Smoke Control Ordinance of Allegheny County, Pennsylvania, was enacted and went into effect on June 1, 1949. The Ordinance has 10 sections which deal with the operation of various equipment in the mills, such as blast furnaces, open-hearth furnaces, by-product coke plants, heating and reheating furnaces, puddling furnaces, smelting plants, bessemer converters, air furnaces and cupolas. The Ordinance provides that a program of research be undertaken to determine practical methods of controlling the emissions caused by blast furnace slips, open-hearth furnaces, and bessemer converters. Reports indicating the status of the research are to be submitted annually to the Bureau of Smoke Control. The Ordinance also permitted the companies to participate in a joint program of research on these subjects if they desired. Accordingly, a joint committee to guide this research was set up between Jones & Laughlin Steel Corporation, National Tube Company, and Carnegie-Illinois Steel Corporation. Members representing operations and research and technology in the various participating companies make up the committee personnel.

After these general considerations of the

pollution abatement problems, let us now take up each specific operation and see what progress is being made in satisfying the requirements of the Smoke Control Ordinance.

## Blast Furnaces

A LARGE modern blast furnace has a daily pig iron output of some 1,400 tons of pig iron. A rough approximation of the daily input to such a furnace would be 2,800 tons of ore and iron-bearing materials, 1,260 tons of coke, 560 tons of a mixture of limestone and dolomite, and 5,000 tons of air. Thus, it can be seen that the raw material used in greatest amount is air, for combustion. The daily output of such a furnace, in addition to the 1,400 tons of pig iron, is approximately 840 tons of slag, 95 tons of coarse flue dust, 45 tons of fine flue dust, and 7,140 tons of blast furnace gas.

From these figures, it can be calculated that the blast furnace gas will contain about three grains of dust per cubic foot after rough cleaning, and that the flow rate will be about 140,000 standard cubic feet per minute, or 200,000,000 cubic feet per day.

A great many installations to clean blast furnace gas have been made, dictated by the desirability of recovering the iron value in the dust and by the use that is to be made of the gas. Such cleaning naturally reduces the atmospheric contamination from blast furnace operation; indeed, in a modern installation the cleanliness of the gas will meet any reasonable standard. Between 18 and 24% of the gas produced by a blast furnace is used in the stoves for heating the air blast. These stoves are brick-lined regenerators, which are alternately heated by the products of combustion of the blast furnace gas and cooled by the passage of air in the opposite direction.

To increase the efficiency of the stove, it is desirable to use brick openings as small as practical. The size of these openings, however, is also governed by the amount of dust in the gas.

It has been found, for example, that gas containing 0.2 grains of dust per cubic foot should not be used in stoves with openings less than 4½ inches square. If the blast furnace gas is cleaned to 0.02 grains per cubic foot, it can be successfully used in checkerwork with openings about 2 inches by 2 inches.

The dust particles in blast furnace gas vary from one-quarter inch to a few microns. The plants, therefore, are arranged to remove the dust in three stages. In the first stage, as the gas leaves the furnace, it goes through a dry dust catcher. The principle involved in its construction is that of greatly reduced velocity accompanied by a sudden change in direction. The coarse dust (60-70% of the total dust) is removed in this operation and is usually sent through a pug mill, where water is added. The wet dust is dropped to a railroad car and taken to a sintering or briquetting plant. If a well-designed cyclone is used in series with the dust catcher, the over-all efficiency can be as high as 90%.

In the second stage of cleaning, commonly called the primary cleaning stage by blast furnace personnel, the dust loading in the gas is reduced to about 0.1 to 0.7 grains per cubic feet. The final stage of cleaning, called the secondary cleaning stage, has as its objective to remove as much of the remaining dust as possible. The secondary cleaners are being operated with final dust loadings of less than 0.001 grains per cubic feet of blast furnace gas.

Many types and combinations of types of cleaners have been used. The primary cleaners include stationary spray towers, revolving spray towers, Feld washers, baffle towers, and spray fans. Primary dry cleaners have included modifications of cyclones, centrifugal machines, filters, and electric precipitators.

For secondary cleaning, wet and dry electric precipitators, Theissen disintegrators, high-speed disintegrators and filters have been used.

In the case of the wet cleaners, the dirty water must be conducted to a thickener or settling basin. The treatment of the recovered dust consists of sintering or briquetting to prepare it for return to the blast furnace. One objection to thickeners is the large ground space required.

Many types of cleaners are in use in Allegheny County. In this area there are 29 blast furnaces, 26 producing basic iron and three producing ferromanganese. Fourteen furnaces are equipped, or soon will be equipped, to clean all the gas produced to at least the equivalent of primary cleaning. It will be noted that the better primary cleaners meet the requirements of most an-

ti-smoke ordinances. The remaining 12 blast furnaces are equipped for gas cleaning in some degree. Most of them are now in their last campaign. When they are replaced or completely rebuilt, they will be equipped with cleaning devices which meet the requirements of the Smoke Ordinance.

This Ordinance establishes the requirements that new or rebuilt furnaces must be equipped with gas cleaning devices to reduce the fly ash content to not more than 0.50 pounds per 1000 pounds of gases, which is the equivalent of about .25 grains of dust per standard cubic foot, except that it shall not be required that the fly ash removed shall be greater than 85% of the total amount present.

Another blast furnace problem that is covered in the Allegheny Ordinance deals with the irregular movements of the furnace burden, called "slips." They are caused by an arching of the furnace charge. The arch finally breaks and the burden slips into the void. There is a rush of gas to the top of the furnace which is often greater than can be handled through the gas-cleaning equipment, and the safety valve opens. The result is a black or red cloud discharged into the atmosphere.

The part of the Ordinance dealing with these "slips" states that all persons responsible for the operations of blast furnaces within the County shall undertake research to determine practical methods of controlling emissions during irregular movements of the furnace burden. As mentioned previously, the status of the research must be reported annually to the Bureau of Smoke Control.

Every blast furnace operator has always been interested in preventing slips, because they make the furnace more difficult to control. Quality and quantity of iron produced suffer. Extensive studies in the past have not let to a solution of this problem, but there is some indication at present that further instrumentation of the blast furnace may help to decrease the number of slips.

Still another problem occurs in the case of furnaces producing ferromanganese. Here we are dealing with the production of a material containing 75-80% manganese. Ferromanganese is used as an addition agent to steel in the open hearth or in the ladle. The blast furnace used is identical with the one used for basic iron. The gas produced is similar in the two cases except that ferromanganese furnace gas has a heating value of about 130 B.t.u. per cubic foot compared to 95 B.t.u. per cubic foot for basic furnace gas.

The amount and types of dust from a ferromanganese furnace are much different from those from a basic blast furnace. Only about 20% of the dust is larger than 20 microns. From the chemical analysis, it has been found that this fraction of the dust is made up mainly of particles of coke and ore. These have apparently been broken off the burden and blown out of the furnace. They are removed from the gas stream by conventional dust catcher and briquetted for return to the furnace.

The rest of the dust is a true fume having particle sizes between one-tenth and one micron. The average particle size is .1 to .5 micron. The manganese content varies from 15 to 25%. A rather unusual feature is the alkali content of from 8 to 15%. The alkalies which are present in the manganese ores are concentrated by the process of vaporization and condensation and form a part of the fume. Recently, Carnegie-Illinois Steel Corporation personnel have undertaken the development of a new process for removing the fume from the ferromanganese blast furnace gas. To determine the practicability of this process and to obtain design information necessary for the large plants required to clean the gas, a pilot plant handling 3,000 standard cubic feet of gas per minute has been installed. It is as yet too early to judge results, but operations to date have been encouraging.

## Open Hearths

THE next step in the production of steel is the open-hearth process, in which the pig iron is refined through the controlled removal of portions of the carbon, silicon, manganese, phosphorus, and sulfur. The furnace, which is lined with refractory brick, contains the charge of pig iron or scrap and pig iron. The heat is supplied by passing burning fuel over the top of the materials. The gas and air for combustion are introduced through ports at either end of the furnace. Firing takes place alternately at one end and then the other. Reversals occur every 15 to 20 minutes. The products of combustion pass out through the exit port, into chambers filled with checker brick,

which absorb some of the sensible heat. The gases then go to the stack. In some cases waste heat boilers are placed between the checkers and the stack. After reversal of flow, the air to be used for combustion passes through the heated checker. The use of checkers increases the heat efficiency and permits the attainment of high temperatures within the furnace.

There are 132 of these open hearth furnaces located in Allegheny County, exclusive of the city of Pittsburgh. The furnaces are fired with oil, tar, natural gas, coke oven gas, and combinations of these fuels. Some furnaces are equipped with waste heat boilers, while others are not.

Because so little is known concerning cleaning open-hearth gas, the Allegheny Smoke Control Ordinance has the following recommendations: All open hearth furnace plants in operation shall incorporate those means of controlling emissions of smoke and fly ash to the atmosphere which have proved to be economically sound. Furthermore, every operator must undertake a research program to determine practical methods of controlling emissions from such furnaces. This research program may be extended for a period of five years and shall be subject to further consideration at the end of the five-year period. Annual reports on the progress of the research are to be submitted to the Bureau of Smoke Control.

The method of operation of an open-hearth furnace as practiced in the Pittsburgh District has been described as follows—the details are given because it was found that the dust loadings vary appreciably during the course of the refining and, accordingly, a sampling program had to be developed that would properly represent the conditions:

Limestone is charged first. Ore is charged on top of the stone and scrap on top of this. Some cold pig iron may be charged with the scrap. The mass is heated until the scrap is slightly fused. This is the melt-down period. Hot metal, which is molten pig iron from the blast furnaces, is then added. This is the hot-metal period.

The refining of the pig iron is brought about through the oxidizing effects of the iron oxides and the fluxing properties of the limestone. Although purification takes place more or less continuously until the heat is tapped, there are distinct phases to the operation, known as ore boil, lime boil, and working period. The ore boil represents the period during which the action of the iron oxide is most important. The condition of charging the limestone on the bottom of the furnace tends to retard its action. When the calcination of this limestone does take place, it is called the lime boil.

The working period is the time after lime boil and preceding tapping of the heat. During this period, the composition of the steel is adjusted and the correct temperature for tapping obtained.

After tapping a heat, the bottom of the furnace must be repaired and preparations made for charging the next heat. This time can be called the rebuilding period.

In summary, the heat has been broken down into six periods: the melt down, hot metal, ore boil, lime boil, working heat, and rebuilding.

A study of dust loadings throughout the various periods of melting and refining in the open hearth has been started by personnel of the Carnegie-Illinois Steel Corporation. The method used for sampling the dust loadings is a modified Brady method. This comprises filtering a metered volume of gas through a paper thimble. From the change in weight of the thimble for a given amount of gas, the dust loading can be calculated.

A large number of samples has been obtained for each period and for a number of different heats in order to find the average and maximum dust loadings. The work done to date has been carried out for the most part on oil-fired furnaces. The dust loadings vary widely, ranging from almost zero to peak loads as high as two grains per cubic foot. Many more samples must be taken before a sufficiently comprehensive evaluation of the dust loadings for the different conditions involved can be obtained.

Some preliminary work on particle size has indicated that approximately 50% by weight of the dust is below 5 microns, with only a few per cent above 20 microns. Chemical analysis shows an iron oxide content of about 90%.

During an open hearth heat, the color of the flue gases coming from the stack varies from white to reddish brown. One point of particular interest here is the lack of correlation between the color and the dust loadings. It was hoped that a modified Rin-

gelmann chart could be developed for the open-hearth. In view of the above this does not appear to be possible. However, the use of a photoelectric cell will be tried in an endeavor to develop a more convenient and less expensive method of sampling stacks.

As soon as the study of open-hearth dust loadings at the various open-hearth shops with their different methods of operation is completed, an investigation of equipment to control the emissions will be undertaken.

It may be well to mention at this time other results which have been obtained on dust loadings from open hearths. Data[1,2] of of this kind obtained at open hearths in Los Angeles County, have been published which show loadings averaging 08 grains per cubic foot, with a maximum loading of two grains per cubic foot. However, because of the nature of the scrap used and the fact that since there is no blast furnace operated in conjunction with the plants, all the metal charge enters the furnaces as scrap, the nature of the dust is quite different from that found in Pittsburgh. Essentially, the dust found in Los Angeles studies is a fume, the particles being mostly below 1 micron in size. The fume contains large amounts of zinc, with only a small amount of iron oxide present.

Published data[3] on the open hearth stack loadings at Donora show a dust loading of only .02-.05 grains per cubic foot, using natural gas as a fuel. Some preliminary data which have been taken in the Pittsburgh District have shown similar dust loadings where gas firing is used. This indicates that gas-fired open-hearths may not contribute appreciably to atmospheric pollution.

The recent practice of using oxygen applied directly to the bath during the working period of the heat to accelerate the reduction process may add a complication. There is a reference in the literature to the use of a Venturi scrubber for removing the dust under these conditions. It is reported that the mean diameter of the particles is in the range of 0.25 to 0.33 microns, on a weight basis, with many particles down in the 0.05 to 0.10 micron range. Efficiencies of 97 to 99.7%, on a weight basis, were reported, but much work remains to be done before the complete story on cleaning open-hearth gas can become known.

## Bessemer Converter

THE principle of operation of the bessemer converter is to refine pig iron by blowing air through the bath of molten metal contained in a vessel. Silicon, manganese, carbon, and a portion of the iron are oxidized. The oxides of the silicon, manganese, and iron form a slag.

One of the great advantages of the bessemer process is its speed. A modern converter produces 25 tons of steel in less than 20 minutes. While we are treated to a colorful spectacle during the blow, it is also apparent that some dust is escaping to the atmosphere.

There does not appear to be a ready answer to this problem. Obviously, the first step is to measure the dust loadings and find the characteristics of the dust, but even this initial step is not easily accomplished. A major difficulty lies in the design of a suitable arrangement to confine the gases for treatment. Wartime experiences in England and Germany may be of some help. However, in these cases it was desired to shield the light of the bessemer rather than to clean the gas.

Because of the anticipated difficulties with cleaning bessemer gas, the Allegheny County Ordinance provides that a research program to determine practical methods of controlling emissions from bessemer converters be undertaken. This research program shall be extended for a period of five years and shall be subject to further consideration at the end of the said five-year period. Reports indicating the progress of the research program shall be submitted annually to the Bureau of Smoke Control.

## By-Product Coke Plants

THE requirement of the ordinance is that all by-product coke plants shall incorporate those means of controlling emissions of smoke and fly ash to the atmosphere which have been proved to be economically practical. The requirement further states that no beehive coke oven shall be permitted to operate within the County.

The coke oven consists of three main parts; namely, the coking chamber, the combustion chambers, and the regenerative chambers—all constructed of brick.

Coal is charged through openings in the top of the ovens to the coking chamber. During this operation, smoke and dust may

be emitted. By proper charging, these emissions may be directed to the closed suction system.

The coal is allowed to remain in the oven for 17 to 20 hours while it is heated by burning gas in the combustion chambers, the heat flowing through the brick wall and into the coal. There is a door at either end of the oven. These are removed at the end of the coking period and a ram pushes the hot coke into a car, which in turn takes the coke to a quenching station.

Elimination of the leaks from oven doors during coking is a problem that has been studied for years. Various types of self-sealing doors have been developed. If they are kept clean and straight, they work well, but maintaining them in this condition is in itself a serious problem because of the high temperatures and frequent handling to which they are subjected. On older ovens, luted doors are used. They must be carefully sealed to give satisfactory performance.

Another source of pollution is the cracking of the oven walls, allowing the volatile products to escape into the combustion chambers. If the crack is relatively small, it may be patched, otherwise the oven must be removed from service and the wall rebuilt.

## Heating and Reheating Furnaces

THERE are over 800 heating and reheating furnaces in the County. More than 96% are fired with natural gas, producer gas, coke oven gas, oil, or combinations of these. It is anticipated that most of the coal-fired furnaces will be changed to burn other fuels in the future. Essentially, therefore, there is no problem with heating and reheating furnaces.

## Sintering Plants

THE section in the Allegheny County Ordinance dealing with sintering plants calls for the use of those means of controlling the emission of smoke and fly ash to the atmosphere which have been proved to be economically practical.

Three sintering plants are being planned or built in Allegheny County. Through careful plant design, and the use of cyclones, the dust will be kept to a minimum.

## Summary

THIS paper has discussed the various types of furnaces and the progress which has been made in satisfying the requirements for metallurgical stacks as set forth in the Smoke Control Ordinance of Allegheny County, Pennsylvania. The paper was restricted for the most part to the work being done in Allegheny County because it is felt that the solutions of the problems in this specific district will be most helpful in other industrial areas.

## Citations

1. JONES, W. P.: *Ind. & Eng. Chem.*, 41, 2424 (1949).
2. MCCABE, L. C., ROSE, A. H., HAMMING, W. J., and VIETS, F. H.: *Ind. & Eng. Chem.*, 41, 2388 (1949).
3. MCCABE, L. C., MADER, P. P., MCMAHON, H. E., HAMMING, W. J., and CHANEY, A. L.: *Ind. & Eng. Chem.*, 41: 2486 (1949).
4. Public Health Bulletin No. 306, Federal Security Agency, Public Health Service, 1949.
5. Smoke Control Ordinance of Allegheny County, Pennsylvania, Enactment Date, May 17, 1949; Enforcement Date, June 1, 1949.

# Gravity and Centrifugal Separation

C. E. LAPPLE,
Engineering Research Laboratory, Engineering Department,
E. I. du Pont de Nemours & Co., Inc.,
Wilmington, Delaware

GRAVITY SETTLING CHAMBERS: The gravity settling chamber is probably the simplest and earliest type of dust collection equipment, consisting of a chamber in which the gas velocity is reduced to enable dust to settle out by the action of gravity. Its simplicity lends it to almost any type of construction. Practically, however, its industrial utility is limited to removing particles larger than 325 mesh (43 microns diameter) since the required chamber size for removing smaller particles is generally excessive. The pressure drop through a settling chamber is small, consisting almost entirely of entrance and exit losses. The most frequent application is on natural draft exhausts from kilns and furnaces due to its low pressure drop and structural simplicity. Gravity collectors are generally built in the form of long empty, horizontal, rectangular chambers with an inlet at one end and an outlet at the side or top at the other end.

A particle will be completely removed if it can settle a height of $H_s$,* in the time it takes the carrier gas to pass from one end of the chamber to the other. Some finer particles that are initially closer to the bottom of the chambers will also be settled out. If this condition is expressed mathematically,[7,9] it will be found that a particle with a terminal velocity of $(q/B_sL_s)$* or larger should be completely settled out. It should be noted that this velocity is the same as that of the fluid if it passed vertically through the area, $B_s L_s$. Thus the performance of a gravity settling chamber depends on its horizontal projected area and is independent of its height. The height need be made only large enough so that the gas velocity, $V_s$, in the chamber is not so high as to cause re-entrainment of separated dust. For this reason, $V_s$ should not exceed about 10 ft./sec.

It is important that the gas be well distributed laterally upon entering the chamber; the vertical distribution is not so important. If the gas is allowed to jet into the chamber, the net effective horizontal projected area available for settling will be less than the horizontal projected area of the chamber. Distribution of the inlet gas can be achieved by gradual inlet transitions, guide vanes, or distributing screens or perforated plates. The outlet can be abrupt without appreciable effect on performance. Curtains, rods, or screens are sometimes suspended in the chamber to minimize eddy currents. They also serve to increase collection and may be equipped with rappers.

While alternately arranged vertical baffle plates causing the gas to undergo a zig-zag path through the chamber have been used in settling chambers on the theory of subjecting particles to changes of direction, their use in simple gravitational settling chambers is generally detrimental since inertial forces are small at velocities usually encountered in such chambers. Horizontal plates arranged as shelves within the chamber, however, will give a marked improvement in collection. This arrangement is known as a Howard dust chamber.[5] For this case it can easily be shown that a particle with a terminal velocity of $(q/N_s\ B_s\ L_s)$ or larger should be completely separated. A Howard chamber can be used to remove particles as small as 10 microns diameter. Its chief disadvantage is in the difficulty of cleaning due to the close shelf spacing and possible warpage at elevated temperatures. This is particularly serious at dust loadings over 1 grain/cu. ft.

## Cyclone Separators

THE most widely used type of dust collection equipment is the cyclone, in which dust-laden gas enters a cylindrical or conical chamber tangentially at one or more points and leaves through a central opening. The dust particles, by virtue of their inertia, will tend to move toward the outside separator wall from which they are led into a receiver. A cyclone is essentially a settling chamber in which gravitational acceleration is replaced by centrifugal acceleration. At operating conditions commonly

*See definition of symbols at end of article.

employed, the centrifugal separating force or acceleration may range from five times gravity in very large diameter, low-resistance cyclones, to 2,500 times gravity in very small, high-resistance units.

*Fields of Application:* Cyclone collectors offer one of the least expensive means of dust or mist collection from both an operating and investment viewpoint. Cyclones have been employed to remove solids and liquids from gases and solids from liquids, and have been operated at temperatures as high as 1000°C, and pressures as high as 500 atm. Cyclones for removing solids or liquids from gases are generally applicable when particles of over 5 microns diameter are involved. Unless very small cyclones are used, the efficiency will be low if much of the suspended material is finer than 5 microns. In collecting particles of over 200 microns diameter, cyclones may be used, but gravity settling chambers are usually satisfactory and less subject to abrasion. In special cases where the dust shows a high degree of agglomeration, or where high dust concentrations (over 100 grains/cu. ft.) are involved, cyclones will remove dusts having a much smaller particle size. In certain cases efficiencies as high as 98% have been realized on dusts having an ultimate particle size of 0.1 to 2.0 microns owing to the predominant effect of agglomeration.

*Flow Pattern:* In a cyclone the gas path involves a double vortex with the gas spiraling downward at the outside and upward at the inside. Upon entering the cyclone, the gas velocity undergoes a redistribution so that the tangential component of velocity increases with decreasing radius. The spiral velocity in a cyclone may reach a value several times the average inlet gas velocity. At the wall the gas velocity approaches zero, whereas it reaches a maximum at a certain radius, decreasing rapidly at smaller radii.[6,9,12,13]

Superimposed on the "double spiral," there may be a "double eddy" similar to that encountered in pipe coils.[14,15] However, such double eddy velocities are small compared to the spiral velocity.

*Friction Loss:* The friction loss through a cyclone is most conveniently expressed in terms of the velocity head based on the immediate cyclone inlet area. The inlet velocity head, in inches of water, is related to the average inlet-gas velocity and density by

$$h_{vi} = 0.00300\ \rho\ V_c^2$$

The cyclone friction loss is a direct measure of the static pressure and power that a fan must develop. The friction loss through cyclones encountered in practice may range from 1 to 20 inlet velocity heads, depending on the geometric proportions.[1,12,13] For a cyclone of specific proportions, however, the friction loss expressed as number of inlet velocity heads, will be substantially constant, independent of the actual cyclone size. For the cyclone of the proportions shown in Fig. 1, the friction loss is approximately eight inlet velocity heads.

*Collection Efficiency:* The performance of a cyclone can be calculated in a manner similar to that used for gravity settling chambers. For a given sized particle to be completely separated, the particle must move rapidly under the action of the centrifugal field from a position on the inner side of the gas inlet duct to the cyclone wall before the gas leaves the cyclone.[7,9,11]

The collection efficiency for particles of various sizes may be represented by a curve of the form given in Fig. 2. This type of plot is essentially a generalized form of the "fractional" efficiency plot frequently found in commercial literature. Fig. 2 gives a plot of the collection efficiency to be expected for various sized particles with a cyclone of the geometric proportions shown in Fig. 1. Particle size is expressed as a ratio to a so-called cut size, $D_{pc}$, which is given by the expression

$$D_{pc} = \sqrt{9\mu\ B_c/2\pi\ N_e\ V_c\ (\rho_p - \rho)}$$

$D_{pc}$ is that sized particle which, with a given dust, is removed or collected to the extent of 50% in a given cyclone at given operating conditions. In other words, the above expression for the cut size makes due allowance for dust properties, gas properties, cyclone size, and operating conditions. The term $N_e$, defined as the effective number of turns made by the gas stream in the cyclone, is actually an empirical quantity which incorporates factors to allow for the complexity of the flow pattern and must be determined experimentally. The value so determined should be unique for any sized cyclone of the same geometric proportions. Similarly, the type of curve given in Fig. 2 must be determined experimentally but,

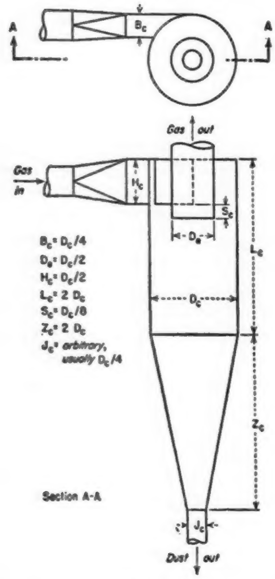


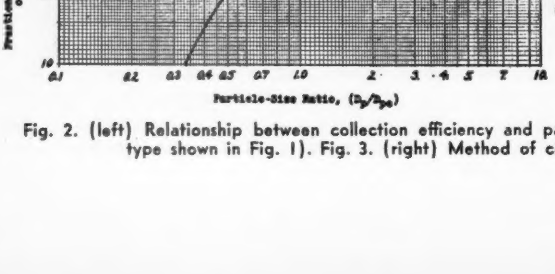

Fig. 1.
Typical cyclone design proportions[9]

once obtained, should be unique for any other cyclone of the same geometric proportions. For a cyclone of the proportions shown in Fig. 1, the value of $N_e$ has been found to be approximately 5 although there have been some indications that it may be as high as 10.

While Fig. 2 gives the collection efficiency to be expected for a given particle size, actual dusts consist of a wide range of particle sizes. Hence, the over-all collection efficiency for an actual dust must be obtained by a summation of the efficiency on each particle size prorated according to the fraction of the total dispersoid in that size range. If the particle size distribution is known, this summation can be carried out graphically by plotting values of $\eta_f$ and $\phi$, corresponding to the same particle size, as ordinate and abscissa, respectively, on arithmetic graph paper. The over-all collection efficiency is then given by the mean ordinate of the plot as shown in Fig. 3. In many cases a good approximation is obtained if the over-all collection efficiency is taken as equal to the cumulative percentage of material in the feed dust, $\phi$, which is larger than the cut size, $D_{pc}$.

The equation for $D_{pc}$ allows for operating temperature in the viscosity term, which means that, for a given inlet velocity, increased temperature results in a larger cut size, corresponding to a lower collection efficiency. As another good approximation, it should be noted that a given size of cyclone will have substantially the same collection efficiency at any temperature, provided the pressure drop is held the same, because of counteracting effects of gas density and viscosity, the cyclone at the higher temperature operating at a higher inlet velocity.

*Cyclone Design Factors:* Cyclones are generally designed to meet specified pressure drop limitations. For ordinary installations operating at approximately atmospheric pressure, fan limitations generally dictate a maximum allowable pressure drop corresponding to a cyclone inlet velocity in the range of 20 to 70 ft./sec. Consequently cyclones are usually designed for an inlet



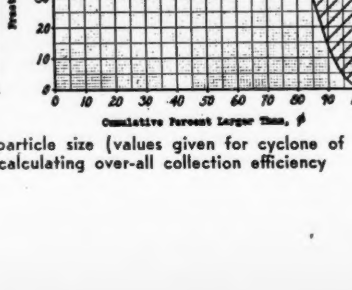




Fig. 2. (left) Relationship between collection efficiency and particle size (values given for cyclone of type shown in Fig. 1). Fig. 3. (right) Method of calculating over-all collection efficiency

velocity of 50 ft./sec., though this need not be strictly adhered to.

In the removal of dusts, the collection efficiency can be changed to only a relatively small amount by a variation in the operating conditions. The primary design factor that can be utilized to control collection efficiency is the cyclone diameter, a smaller diameter unit operating at a fixed pressure drop having the higher collection efficiency but requiring a multiple of units in parallel for a specific gas handling capacity. The final design involves a compromise between collection efficiency and complexity of equipment. It is customary to design a single cyclone for a given capacity, resorting to multiple units only if the predicted collection efficiency is inadequate for a single unit. Cyclones in series are generally not justified. Exceptions to this are cases where the dust is fine and has a relatively uniform particle size distribution, and where the dust is present in a highly flocculated state. In the latter case efficiencies predicted on the basis of ultimate particle size distribution will be highly conservative. Also, while normally efficiency is increased by increasing the gas through-put, in such cases the reverse may be the case due to the deflocculating effect of higher velocities.

Reducing the gas outlet duct diameter will increase both collection efficiency and pressure drop. Increasing the length of a cyclone is generally believed to increase collection efficiency though there are no reliable supporting data. There is also no reliable information on the effect of inlet proportions or cone angle on collection efficiency.

A cyclone will operate equally well on the suction or pressure side of a fan if the dust received is air-tight. Probably the greatest single cause for poor cyclone performance, however, is the leakage of air into the dust outlet of the cyclone. A slight air leak at this point can result in a tremendous drop in collection efficiency, particularly with fine dusts. For a cyclone under pressure, air leakage at this point is objectionable primarily from the local dust nuisance created. For batch operation an air-tight hopper or receiver may be used. For continuous withdrawal of collected dust, a rotary star valve, a double-lock valve, or a screw conveyor may be used, the latter only with fine dusts; a liquid seal leg is sufficient for mist or spray collectors. In any case, it is essential that sufficient unloading and receiving capacity be provided to avoid collected material from accumulating in the cyclone cone.

Generally cone and disk baffles, helical guide vanes, straightening vanes, etc., placed inside a cyclone, will have a detrimental effect on performance. A few of these devices have merit under special circumstances. An inlet vane, formed by extending the inner side of the inlet duct past the cyclone wall to the gas outlet duct, has been found to reduce the friction loss through the cyclone by over 50%.[1,12] However, a correspondingly greater reduction in collection efficiency results. The $N_e$ value for this arrangement is approximately 2 for cyclone inlet velocities on the order of 50 ft./sec. Such a vane is only recommended (a) where collection efficiency is normally so high as to be of secondary importance, (b) where it is desired to decrease the resistance of an existing cyclone system for purposes of increased air handling capacity, or (c) where floorspace or headroom requirements are controlling factors. If an inlet vane is used, it is advantageous to increase the gas exit duct length inside the cyclone chamber. A disk or cone baffle located beneath the gas outlet duct may be beneficial if air inleakage at the dust outlet cannot be avoided. A heavy chain suspended from the gas outlet duct has been found useful in minimizing dust buildup on the cyclone walls. At present there are no known devices which will recover the velocity energy of gas spiralling in the gas outlet duct. Substantially all devices which have been reported to reduce pressure drop do so by reducing spiral velocities in the cyclone chamber and consequently result in a reduced collection efficiency.

Increased dust loading will result in both decreased pressure drop and increased collection efficiency. At dust loadings of over 200 grains/cu.ft., the pressure drop may be as low as half of that calculated in the absence of dust.

*Commercial Equipment:* Simple cyclones are available in a wide variety of shapes ranging from long slender units similar to that shown in Fig. 1 to short large-diameter units. The body may be conical or cylindrical and entrances may be involute or tangentials and round, oval, or rectangular, and single or multiple in number. Some of the

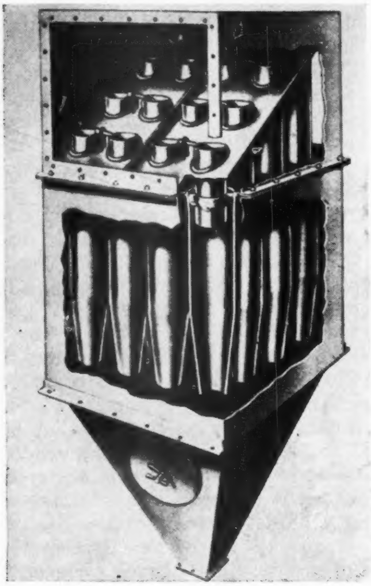


Fig. 4.
Multiclone (Western Precipitation Corp.)

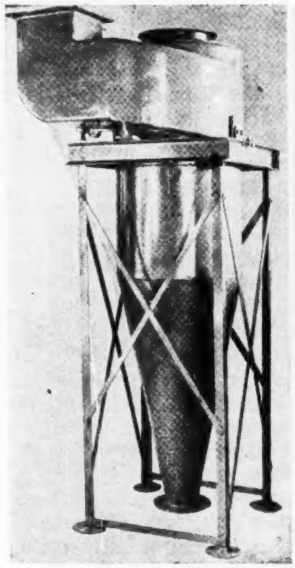


Fig. 5. (left) Multicyclone (Prat-Daniel Corp.)
Fig. 6. (right) Thermix tube (cutaway view of ceramic unit—Prat-Daniel Corp.)

manufacturers of such cyclones are Bartlett & Snow, Buffalo Forge, Clarage, The Day Co., Gruendler, Gump, Hardinge, Pangborn, Sturtevant, Williams, and Wolf.

In Figs. 4 to 9 are shown some of the special types of commercial cyclones. The Sirocco Type D cyclone (Fig. 7) has an exit-duct dollar that can be changed to increase or decrease collection efficiency with a corresponding increase or decrease in pressure drop. The Multicyclone (Fig. 5) is furnished in multiple units of 2 or 3 ft. diameter cyclones, each containing an adjustable inlet damper to compensate for variations in gas through-put. In the Multiclone (Fig. 4) a spiral motion is imparted to the gas by annular vanes, and it is furnished in multiple units of 6 and 9 in. diameter. The Van Tongeran cyclone (Fig. 8) claims to utilize the "double eddy" for increased collection efficiency by providing a by-pass from the top to the conical portion of the cyclone. The Thermix unit (Fig. 6) comprises 6-in. diameter units in parallel and is available in ceramic as well as metallic construction. The Sirocco fly ash collector (Fig. 9) consists of horizontal tubes, approximately 15 in. diameter and 6 ft. long in parallel. The gas is given a spiral motion by vanes located in the inlet at the left, and the dust

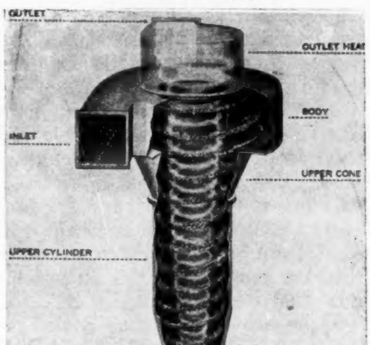



Fig. 7.
Sirocco Type D Collector (diagrammatic cutaway view—American Blower Corp.)

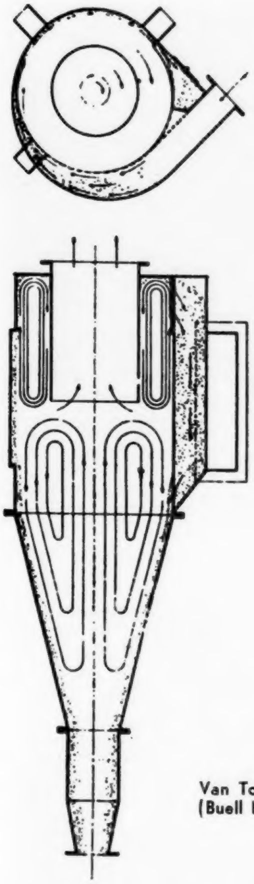


Fig. 8.
Van Tongeren Cyclone
(Buell Engineering Co.)

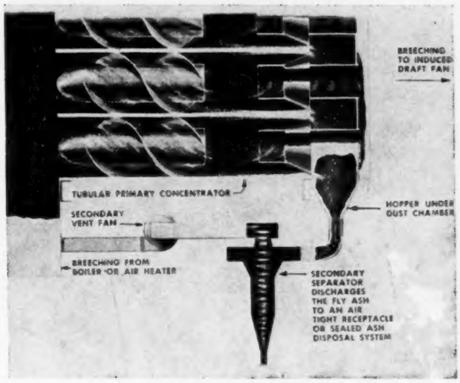



Fig. 9.
Sirocco Type ST Fly Ash Collector (American Blower Corp.)

is concentrated in a small portion of gas which is re-circulated through a smaller secondary cyclone separator for final collection of the dust. A recent development is the Aerotec tube[8] consisting of multiple units of 2 or 3-in. diameter similar in shape to the Thermix tube. Smaller diameter units are also made for special applications.

*Entrainment Separation:* Cyclones may also be used to separate liquid droplets from gases. In this connection they find their most frequent application in the removal of mechanical entrainment from such equipment as distillation and absorption columns and evaporators. The collection efficiency on mists formed by vapor-phase reaction or condensation will generally be low owing to the small particle size involved. In the case of mechanical entrainment, the particles are predominantly larger than 100 microns diameter and complete separation is a simple problem. Any inefficiency in such service is not due to a failure to collect all the spray on the wall but to re-entrainment or wall creep of the liquid film after the spray has been deposited on the cyclone wall.[10] The liquid film may be carried across the cyclone roof to the gas outlet by the action of the "double eddy." The film will then run down the outside of this duct and be carried out of the cyclone. In the case of dusts such action will not occur since the dust cannot adhere to the exit duct as a mobile film. With liquids this action can be minimized by providing either a concentric cylindrical shield around the gas outlet duct or a conical skirt fastened to the outside of the gas outlet duct some distance above its mouth. These arrangements avoid carry-over by providing a drip point before the liquid is exposed to the outlet gas stream. In either case the cyclone diameter should be enlarged over that of a corresponding dust cyclone to avoid direct impingement of the inlet gas stream on the shield or skirt. A cyclone of the type shown in Fig. 1 equipped in this fashion should remove over 98% of mechanical entrainment, provided the inlet gas velocity is maintained less than 150 ft./sec. for operation with air at atmospheric pressure. For high gas densities lower limiting velocities will apply. Also, if the liquid loadings are very high, as in flash evaporators, lower inlet velocities should be used, since the high

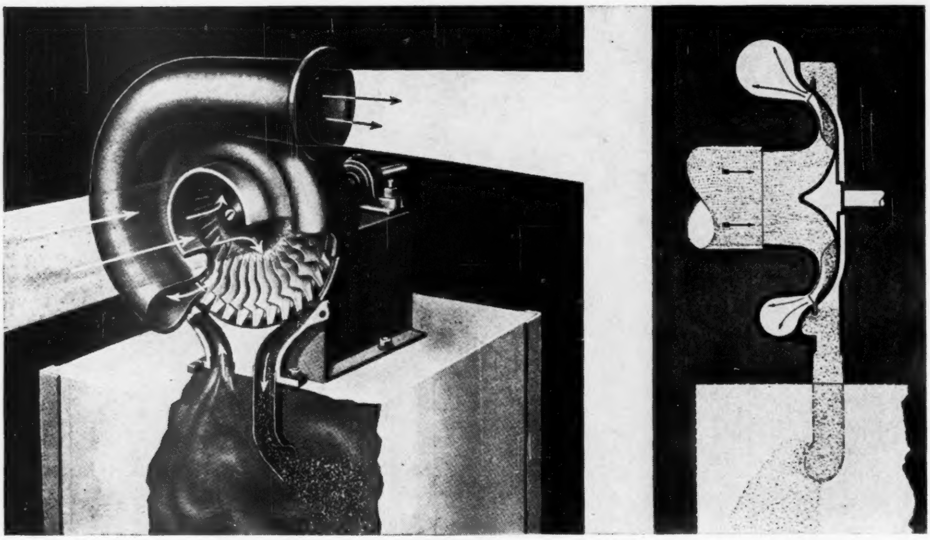


Fig. 10.
Type D Rotoclone (American Air Filter Co.)

liquid loading will upset the spiral path of the gas in the cyclone and accentuate the re-entrainment tendencies. If the shield or skirt is omitted, the carry-over from the cyclone may increase five to tenfold.

For the separation of mechanical entrainment, cyclones arranged in parallel will serve no useful purpose unless headroom is a prime consideration. With cyclones in series, however, very high degrees of spray elimination can be achieved.

## Mechanical Centrifugal Separators

A NUMBER of collectors are commercially available in which the centrifugal field is supplied by a rotating member. Typical units are shown in Figs. 10 and 11. In the Rotoclone the exhauster or fan and dust collector are combined as a single unit. The blades are especially shaped to direct the separated dust into an annular slot leading to the collection hopper while the cleaned gas continues to the scroll. The Sirocco cinder fan consists of a dust collector located on the inlet side of a fan with the dust collector rotor connected to the fan shaft. The dust-laden gas enters on the periphery of the scroll, passing radially inward through the rotor and out the center, which point is normally coincident with the fan inlet port. Dust thrown to the scroll wall is concen-

Fig. 11.
Sirocco Cinder Fan (American Blower Corp.)

trated in a small stream of gas which is bypassed through a cyclone collector, where the dust is finally collected.

Although no comparative data are available, the collection efficiency of units of this type is probably comparable to that of a single-unit, high pressure-drop cyclone installation. The clearances are smaller and the centrifugal fields higher than in a cyclone, but these are probably compensated for by the shorter gas path and greater degree of turbulence with its inherent re-entrainment tendency. The chief advantage of these units lies in their compactness, which may be a prime consideration for large installations or plants requiring a large number of individual collectors. Caution should be exercised when attempting to apply this tendency to build up on solid surfaces because of the high maintenance costs from plugging and rotor unbalancing.

## Numerical Examples

I. GRAVITY SETTLING CHAMBER: It is proposed to install a Howard gravity collector, 12 ft. wide x 10 ft. high x 20 ft. long with a 1-in. shelf pitch, to remove 62° Bé. sulfuric acid mist from 1000 cu.ft./min. of converter gases (substantially air) at 70°C. Estimate the smallest diameter, in microns, of mist droplet that should be completely removed by this chamber.

*Solution:* From conditions of the problem:

$\rho_p = 62°$ Bé $= (1.747)\ (62.3) = 108.8$ lb./cu. ft.

$\rho = 0.0644$ lb./cu. ft.

$\mu = 0.0204$ cp.$= 1.37\times10^{-5}$ (lb.) / (ft.) (sec.)

$N_s = (10)\ (12) / (1) = 120$

$q = (1000) / (60) = 16.67$ cu.ft./sec.

$B_s = 12$ ft.; $H_s = 10$ ft.; $L_s = 20$ ft.

From equation: $u_{tg} = q/N_s\ B_s\ L_s$

$u_{tg} = (16.67) / (120)\ (12)\ (20) = 0.000579$ ft./sec.

From Stokes's law

$$D_{p,min} = \sqrt{\frac{(18)\ (1.37\times10^{-5})\ (0.000579)}{(32.17)\ (108.8)}}$$

$$= 0.638\times10^{-5} \text{ ft.} = 1.94 \text{ microns}$$

II. CYCLONE SEPARATOR: Design a cyclone to handle 1900 cu.ft./min. of ventilation air from a talc dusting booth at a friction loss of 3 in. water. Estimate the collection efficiency assuming the dust to have the following Roller analysis based on a true particle specific gravity of 2.6. Assume an air temperature of 70°F.

| Particle Diameter, microns | Cumulative Per Cent Larger Than |
|---|---|
| 5 | 79.7 |
| 10 | 60.2 |
| 20 | 25.5 |
| 40 | 1.8 |

From the conditions of the problem

$q = 1900$ cu.ft./min. $= 31.7$ cu.ft./sec.

$\rho = 0.0749$ lb./cu.ft.

$\rho_p = (2.6)\ (62.3) = 162.0$ lb./cu.ft.

$\mu = 0.0181$ cp. $= 1.22\times10^{-5}$ (lb.) / (ft.) (sec.)

Inlet velocity $= \sqrt{(3) / (0.003)\ (0.0749)\ (8)} =$ 40.8 ft./sec.

Inlet width $= \sqrt{(31.7)\ (144) / (2)\ (40.8)} =$ 7.5 in.

Required cyclone dimensions (from Fig. 1):

Inlet: 7½ in. wide x 15 in. high
Diameter: 30 in.
Cylinder height: 60 in.
Cone height: 60 in.
Gas exit duct diameter: 15 in.
Gas exit duct length: 19 in.
Dust outlet diameter: 6 in.

Inlet area $= (7.5)\ (15) / (144) = 0.781$ sq.ft.

Inlet velocity $= (31.7)/(0.781) = 40.6$ ft./sec.

$$D_{pc} = \sqrt{\frac{(9)\ (1.22\times10^{-5})\ (7.5)}{(12)\ (2)\ (3.14)\ (5.0)\ (40.6)\ (162.0)}}$$

$$= 1.823\times10^{-5} \text{ ft.} = 5.56 \text{ microns}$$

The following tabulation can be prepared from the values given in Fig. 2 used in conjunction with a plot of the particle size analysis given above:

| $D_p/D_{pc}$ | $\eta_f$, % | $D_p$ microns | $\phi$, % |
|---|---|---|---|
| 0.2 | 4 | 1.11 | 95.0 |
| 0.3 | 8 | 1.67 | 92.7 |
| 0.5 | 20 | 2.78 | 88.2 |
| 0.7 | 33 | 3.89 | 84.0 |
| 1.0 | 50 | 5.56 | 77.2 |
| 1.5 | 69 | 8.34 | 66.7 |
| 2.0 | 80 | 11.1 | 56.0 |
| 3.0 | 90 | 16.7 | 35.0 |
| 5.0 | 96 | 27.8 | 10.3 |
| 7.0 | 98 | 38.9 | 2.1 |
| 10.0 | 99 | 55.6 | 0.1 |

Plotting $\eta_f$ as ordinate against $\phi$ as abscissa (see Fig. 3), the over-all collection efficiency is found from the mean ordinate to be 70%.

## Nomenclature

$B_c$ = width of rectangular cyclone inlet duct, ft.

$B_s$ = width of gravity settling chamber, ft.

$D_p$ = diameter of particle, ft.

$D_{pc}$ = cut size, diameter of particles of which 50% of those present are collected, ft.

$D_{p,\,min}$ = minimum diameter of particle which is completely collected, ft.

$h_{vi}$ = velocity head of fluid, in. water

$H_s$ = height of gravity settling chamber, ft.

$L_s$ = length of gravity settling chamber in direction of gas flow, ft.

$N_e$ = "effective" number of turns made by gas stream in a cyclone separator, dimensionless

$N_s$ = number of horizontal shelves parallel to gas flow in gravity settling chamber, dimensionless

$q$ = gas flow rate, cu. ft./sec.

$t$ = time, sec.

$u_{tg}$ = gravitational settling velocity of smallest particle completely settled out in gravity settling chamber, ft./sec.

$V_c$ = average cyclone inlet velocity, ft./sec.

$V_s$ = average gas velocity in gravity settling chamber, ft./sec.

$\rho$ = fluid density, lb./cu. ft.

$\rho_p$ = true (*not* bulk) density of particle, lb./cu. ft.

$\eta_f$ = fractional collection efficiency, weight percent of entering dispersoid of specific size collected, dimensionless

$\phi$ = cumulative weight percent in entering dispersoid larger than a given particle size, dimensionless

$\mu$ = fluid viscosity, lb./(ft.) (sec.)

## Citations

1. ALDEN, J. L.: "Design of Industrial Exhaust System." Chap. VI, Industrial Press, New York, 1940.
2. ANDERSON, E.: *Chem. & Met. Eng.*, 40:525 (1933).
3. DRIJVER, A.: *Waerme*, 60:333-39 (1937).
4. FEIFEL, E.: *Forsch. Gebiete Ingenieurw.*, 9:68-81, 306-8 (1938); 10:212-19 (1939).
5. HOWARD, H.: Fume Arrestor, U.S. Patent No. 896, 111 (1908).
6. LARCOMBE, H. L. M.: *Ind. Chemist*, 18:433-8, 477-83 (1942); 19:25-8 (1943); *Mining Magazine*, 77:137-48, 208-17, 273-8, 346-7 (1947).
7. LAPPLE, C. E.: "Dust and Mist Collection." Lecture notes, March, 1948, University of Delaware (to be published by University of Delaware).
8. PARENT, J. D.: *Trans. Am. Inst. Chem. Engrs.*, 42:989-99 (1946).
9. PERRY, J. H.: "Chemical Engineers' Handbook," 2nd Ed., 1941, pp. 1850-84; 3rd Ed., pp. 1013-1050, New York, McGraw-Hill Book Co.
10. POLLAK, A., and WORK, L. T.: *Trans. Am. Soc. Mech. Engrs.*, 64:31-41 (1942).
11. ROSIN, P., RAMMLER, E., and INTELMANN, W.: *Z. Ver. deut. Ing.*, 76:433-7 (1932).
12. SHEPHERD, C. B., and LAPPLE, C. E.: *Ind. Eng. Chem.*, 31:972-84 (1939); 32:1246-8 (1940).
13. STAIRMAND, C. J.: *Engineering* (London), 168: 409-12 (1949).
14. VAN TONGEREN, H.: *Mech. Eng.*, 57:753-9 (1935).
15. WELLMANN, F.: *Feuerungstech.*, 26:137-45 (1938).
16. WHITON, L. C.: *Trans. Am. Soc. Mech. Engrs.*, 63:213-8 (1941); *Mech. Eng.*, 65:885-8 (1943); *Power Plant Eng.*, 47:92-5 (December, 1943); *Power*, 88: 20-1 (1944); 75:344-6 (1932); *Chem. & Met.*, 39:150-2 (1932).

# Smoke

J. W. SHAW,
Chief Smoke Inspector,
Bureau of Smoke Inspection and Abatement,
Department of Buildings and Safety Engineering,
Detroit

THE subject for this period is SMOKE. In order to become completely familiar with the problem of smoke, and the various types of equipment in which fuel is used, years of experience in combustion engineering are required, with much time spent in search of practical measures designed to combat our smoke menace. We can, in the time allotted, explore only the salient points involving the emission of smoke as a result of the combustion of fuel for heat and power, to the exclusion of incineration and fly ash.

Smoke regulations are not new. The first known regulations were administered in England during the latter half of the 13th century. These first laws were indeed fuel restrictive ordinances, and much more severe in the penalties meted out for infractions than those enforced today. Equipment was confiscated and destroyed whenever it was discovered that "sea coal" was consumed in it. Smoke control laws passed during the last decade are again approaching these first laws in scope and severity. The need for these recent and more stringent ordinances becomes more apparent when one learns that the ordinances which were passed in the intervening 700 years were complied with, but the air pollution in our urban communities continued unabated.

What is smoke? Smoke is a product of combustion in the form of a mass consisting of very fine particles or molecules of free carbon suspended in a mixture of air and gas. It is visible because of its density which varies with the concentration of its solid particles.

There are some solid fuels, such as, anthracite, devolatilized coal (coke) and wood (charcoal) that cannot be made to produce dense black smoke no matter how they are burned. If smoke consists of molecules or minute particles of carbon, and we cannot induce the fuels just mentioned to produce smoke, even though they represent an almost pure form of carbon, how is smoke produced? The answer lies in the fact that smoke results from the heating of hydrocarbons in an atmosphere which is deficient in the supply of oxygen.

Most people think of oil and gas as smokeless fuels. This is far from true. Both of these fuels can give off dense smoke. In fact, most of today's commercial carbon black (known as "lamp-black") is manufactured by burning natural gas with a deficiency of oxygen. I'm sure you have all seen pictures of oil tanks or refineries burning with the resultant clouds of dense black smoke billowing upwards.

There are three broad basic causes for smoke: Improper equipment, faulty operation, and unfit fuel. With reference to the requirement for proper combustion conditions, most authorities prescribe the application of the three "T's"—Time, Temperature and Turbulence. I prefer to remember but "TO" conditions—Temperature and Oxygen. They are as inseparable as Siamese twins where smokeless and efficient combustion is to take place. In other words, sufficient temperature may be provided, but a deficiency of oxygen will result in the production of smoke. An adequate supply of oxygen may be provided but the temperature may be too low, and this condition will also result in smoke. But, where both are present in the proper proportionate quantities, the result is efficient and smokeless operation.

Owing to the physical characteristics of oil and gas, it is simple to design equipment that will burn them smokelessly. This type of equipment is quite foolproof and can usually be operated smokelessly in normal installations.

We have previously mentioned the reasons why anthracite or coke cannot be burned so as to produce dense smoke. That brings us to the chief cause of smoke as we have defined it in this paper which is our old friend of 700 years ago, "sea coal" or bituminous coal as it is known today. Probably the one characteristic of bituminous coal, which is the major contributing source of smoke in all these years, is the fact that it can be so easily kindled and burned without any

special skill or automatic equipment. But, where proper equipment is installed and maintained, bituminous coal can be burned smokelessly. The quantity of smoke emitted from bituminous coal generally varies directly with the per cent or ratio of the volatile content in the coal. However, actual burning tests have been conducted which demonstrate that there are some exceptions to this generality. It is quite obvious that there is a great need for more research in order to determine the nature of the volatiles in coal.

A FEW words should be said about the various panacea chemicals placed on the market which are intended for use with coal to prevent soot or smoke. Most of these chemicals are fakes, being over-priced colored salts. There are known chemicals that will speed the combustion processes. But complete, efficient and smokeless combustion can be accomplished by the proper installation of adequate equipment properly maintained and operated with the use of the kind of fuel for which the equipment was designed. We have observed many tests where these additives were used. None of them observed to date was found deserving of serious consideration.

SO FAR, we have covered our topic in an introductory manner. The following will be predicated on specific fundamentals as to equipment, fuels, and operation.

First, the basic reason for the burning of fuel is to obtain the resultant useful heat. A full understanding of this fundamental concept calls for careful consideration in the selection of proper fuels, equipment, and operating practices to meet the requirements for heat and power loads. Smokeless combustion meets these requirements most efficiently. The economics of specific fuel prices will guide the selection of fuel on a "useful BTU produced" basis, rather than on a "BTU available in the fuel" or a "cost per ton" basis. In other words, there is a tendency to place the cart before the horse.

Secondly, the method of transmitting the heat from the combustion chamber where it is created to the heat-absorbing fluid (liquid or gas) varies widely with a designer's choice in meeting the heat and power requirements.

There are common types of boilers and furnaces, as well as many more types of special heat transfer equipment in contact with combustion gases.

One method of classifying common types of boilers and furnaces is by the heat-absorbing medium. In that case the equipment would be known as warm air, hot water, or steam systems.

Another method of classifying common types of boilers and furnaces is by the material of which they are made, such as, cast iron, steel, or those known as refractory types.

Most of the special types, such as the latter mentioned, are found in industrial process work. Some types can be quickly named: Refinery heaters, open hearths, blast furnaces, coke ovens, brick kilns, heat treat furnaces, direct-fired stills, and bessemers, among others.

## Bibliography

1. HASLAM and RUSSELL: Fuels and Their Combustion. McGraw-Hill Company, 1926.

2. ARTHUR D. PRATT: Principles of Combustion in the Steam Boiler Furnace. Babcock and Wilcox Company.

3. DE LORENZI, OTTO: Combustion Engineering. Combustion Engineering-Superheater, Inc., 1949.

4. BECK, CLARENCE VICKERS: Modern Combustion, Coal Economies, and Fuel Fallacies. Mid-West Coal Retailer, Chicago, 1931.

# Atmospheric Pollution Control in Petroleum Refineries


LEWIS J. CRALLEY,
Senior Scientist, U. S. Public Health Service,
Chief, Environmental Investigations Branch,
Division of Industrial Hygiene,
Washington, D. C.


THE increased mechanization of our industry together with our rising standard of living have necessitated an enormous increase in the production of petroleum products during the past decade. This is reflected in data issued by the Bureau of Mines, which show that the crude oil through-put capacity in refineries increased from around four and a half million barrels per day in 1939, to almost six and a half million barrels per day in 1949. The production of cracked gasoline increased from approximately a million barrels per day in 1939 to around a million and three-quarter barrels per day in 1949. These figures do not take into consideration the large expansion in construction in 1949. With the tremendous increase in production in this industry and similar increase in activities in other industries it is not surprising that problems of atmospheric pollution may now be arising which heretofore were of little notice.

It is not within the scope of this paper to discuss, technically, processes relating to refinery operations. The discussion will be limited to some of the major contaminants encountered which may be released in significant quantities into the air, the processes and operations involved, and means of minimizing or controlling the problems.

## Nature of Contaminants Emitted

THE control of sulfur gases is one of the major atmospheric pollution problems in petroleum refining. Crude oils vary greatly in sulfur content, ranging from a fraction to a percent in Pennsylvania fields to over 5% in some of the Mexican fields. The sulfur may exist as hydrogen sulfide or as organic compounds, such as mercaptans, mono- and di-sulfides, and thiophenes. Air pollution from sulfur compounds is generally limited to hydrogen sulfide, highly volatile organic compounds, and sulfur dioxide resulting from burning these gases.

Crude oils also contain considerable quantities of inorganic materials. This inorganic material will vary widely both in composition and amounts depending on the source and the basic type of the crude. Arsenic, phosphorus, silicon, vanadium, lead, manganese, chromium, barium, strontium, nickel and titanium are only some of the elements which have been found in crude petroleum. These elements may exist as organic as well as inorganic compounds. Considerable quantities of sodium and calcium chloride are also found in crude oils. It is possible that some of these elements may be transformed through refinery conversion processes, such as catalytic cracking, into volatile compounds and eventually escape into the air. They are also liberated during the burning of heavy residues which are used as fuels, or in acid sludge burning.

The heavy demand for gasoline, along with other desired products for domestic and industrial use, made it necessary to devise means of converting as much of the crude oil as possible into these products. This led to the employment of a number of catalytic processes which are used routinely in present-day refinery operations. The following are mentioned merely to give an idea of the many processes and variety of catalysts used: in catalytic cracking—aluminum chloride, alumina-silica, activated clays, bauxite and molybdena-alumina; in hydrogenation—vanadium, chromium, cobalt and aluminum oxides. Catalytic processes are also in use which convert the gaseous fractions of the crude oil into higher boiling fractions such as gasoline. Examples of these processes and the catalysts used are: *alkylation*—sulfuric acid, hydrofluoric acid, boron trifluoride, aluminum chloride; *isomerization*—aluminum chloride and bromide with hydrogen chloride, boron trifluoride with hydrogen fluoride, aluminum chloride and antimony chloride; *polymerization*—sulfuric acid, phosphoric acid, boron fluoride, aluminum chloride, copper pyrophosphate. Any one refinery may use several of the above processes, depending on the nature of the

available crude oil fraction and the product desired. Generally speaking, catalysts of various types may escape into the air either as a carry-over with gaseous compounds or in regeneration processes, depending on the nature of the process and the catalyst. Small amounts of catalysts which may remain in the residue would also be emitted into the air if the residue is burned.

Other less significant contamination of the atmosphere may arise from numerous leaks and spills throughout the refinery area; oil mists around leaky distillation equipment; processing of petroleum chemical products; and maintenance and repair shop operations, such as sand-blasting and spray painting.

### Control of Processes Emitting Contaminants

CRUDE OIL STORAGE: Tank farms and other locations where sour crude oils are received and stored may present a serious atmospheric pollution problem. Hydrogen sulfide and highly volatile organic sulfur compounds escape from the crude oil and collect at the top of the storage vessels. These gases are released to the atmosphere during filling operations and in the breathing phenomenon of the tanks resulting from temperature changes. Health hazards and nuisances have been ascribed to toxic gases from these sources. There are also records of the darkening of lead base paints on houses downwind of these areas.

One method for controlling this hazard is to vent the tanks and flare the gases. Where several tanks are located together, the vents may be connected to a common header and flared. The gases are thus converted from highly toxic ones to the less toxic sulfur dioxide. Where this method is used, it should be ascertained that the sulfur dioxide is not released in quantities to create a health hazard or nuisance. Another method, which provides a more positive means of control, is to pass the gases vented from the tanks through an alkali scrubber. This method is described in more detail later in this paper.

### Primary Fractionation

IN THE primary fractionation, only a small proportion of the total sulfur is released from the crude oil. The sulfur compounds are thus concentrated in the high boiling fractions and may range as high as 10%, whereas the crude oil contains only a small percentage of sulfur. Considerable quantities of sulfur gases are nevertheless released during primary fractionation. They are principally hydrogen sulfide with some highly volatile organic compounds such as mercaptans.

The removal and disposal of these gases during this process will be discussed in some detail at this time since frequent mention will be made of these methods in the control of similar contaminants encountered at other processes. With present-day production it is generally unsatisfactory to vent and flare the gases from this process. This method would be applicable only in a case of extreme isolation of the refinery and strict control and selection of the source of the crude oil. Effective methods have been worked out for preventing the escape of these gases into the air. If there is no desire to reclaim and use the sulfur, these gases may be removed by passing them through conventional scrubbers using a caustic solution. In some instances the scrubbers may be operated under pressure. The excess alkali from this process may be used to neutralize acid sludges.

Another method which has operated successfully in the control of these gases permits the reclaiming of the sulfur. In general, the method involves passing the gases through a conventional type scrubber under pressure and reacting the sulfur gases with a basic substance from which it may later be removed. Tripotassium phosphate is an example of an inorganic salt used in this method. The hydrogen sulfide is stripped from the solution by heating and the regenerated tripotassium phosphate returned to the scrubber. Organic bases have also been used successfully. An example is the use of diethanolamine. The hydrogen sulfide is removed from the petroleum vapors by passing the mixtures through a scrubber under pressure using diethanolamine. The hydrogen sulfide is subsequently stripped from the extraction medium by means of steam and the regenerated diethanolamine returned under pressure to the scrubber. The hydrogen sulfide reclaimed through these processes may be burned and converted to sulfuric acid, or a portion of it may be burned and the resulting sulfur dioxide reacted with hydrogen sulfide to form elemental sulfur.

### Conversion Processes

AS MENTIONED earlier, the great demand for specific petroleum products such as gasoline and other fuels makes it necessary to convert as much of the crude oil as possible into these products. In some instances this means the breaking down of high boiling fractions through thermal and catalytic cracking. In other instances the gaseous hydrocarbons are converted into higher boiling fractions.

Only scant information is available as to the atmospheric pollution problems associated with these processes. It is a realm within which intensive investigative work needs to be done in order to define the problems and work out control procedures.

As previously indicated, the sulfur compounds in the crude oils tend to concentrate in the high boiling fractions during primary fractionation. It is these high boiling fractions that are cracked to give converted products such as gasoline. With the tremendous increase in cracked gasoline production, it can readily be seen why the control of the sulfur gases is important in the prevention of air pollution. The various products from the cracking units are separated by passing the complex mixture through fractionating units. The hydrogen sulfide may be handled from these units in a way similar to that described earlier under primary fractionation. Mention has also been made of the many inorganic constituents found in crude oil. It is not known to what extent these materials may enter into the complex reactions of cracking and hydrogenation processes and thus reconvert into volatile compounds and escape into the air. In many instances it is a practice to water wash the crude to remove excessive amounts of salt that may be present. This is necessary to protect the equipment.

The handling of the catalysts may present a problem. This is especially true in regeneration processes. This problem is likewise in need of further investigation both in order to define its magnitude and to develop indicated control procedures.

### Purification Processes

NUMEROUS methods have been developed for purifying petroleum products before placing them on the market in order to stabilize the product and to give better physical properties, such as odor and color.

One of the most common methods is to treat the product with sulfur acid. This removes various sulfur and resinous materials as well as certain aromatic and unsaturated hydrocarbons. The residual acid sludge contains a high percentage of acid and should have special treatment. The sludge may be diluted and blown with air, thus stripping out a large percentage of the sulfur dioxide which is reconverted to sulfuric acid. The disposal of the sludge will be discussed later.

Other processes for removing sulfur compounds include such methods as low temperature catalytic procedures and hydrogenation. The hydrogen sulfide released during these operations may be captured and handled similarly to methods described under primary fractionation.

Mercaptans and hydrogen sulfide may also be scrubbed out of such products as gasoline through treatment in scrubbing towers containing alkaline solutions combined with other compounds such as methanol, potassium isobutyrate, glycols or diamines. The sulfur compounds are then removed by stripping and the alkali solution returned to the scrubber. Adaptation of methods previously discussed may be used to prevent the sulfur gases from escaping.

### Storage of Finished Products

IN THE storage of volatile products, tanks receiving these materials are usually provided with floating roofs to take care of vapors displaced during filling operations and surging due to the breathing phenomenon of the tanks. Where several tanks are located in the same area, they may be vented to a common header and connected to a single tank with a balloon type floating roof. In many instances, the product may be given an additional treatment such as doctor sweetened with sodium plumbite in order to improve its stability. However, on long standing the reaction may be somewhat reversible, and hydrogen sulfide and mercaptan odors develop. Should this occur, the product may be retreated. A quick turnover, however, is the best solution.

### Miscellaneous

THE disposal of waste acid sludge is a difficult problem. In general, it is an unsatisfactory method to burn it in an open pond. These sludges have a very high sulfur

content and release a considerable amount of sulfur dioxide into the air when burned in the open. They may also contain varying amounts of organic and inorganic materials which may be released into the air. The burning of this sludge should be done under controlled conditions and the resulting contaminants passed through collectors.

It is a common procedure to use high boiling fractions of the crude along with that from the cracking operation, as well as acid sludge, as a source of fuel for the refinery. These products may be high in sulfur content. They will also contain inorganic substances which were present in the crude oil as well as some of the catalysts used in the processes. If the sulfur content of the fuel is high, it may be necessary to remove the sulfur dioxide released through burning these fuels by passing it through an alkali scrubber. The possible significance of the volatilization and emission of the other material present in the fuel has not been determined. This problem should be investigated.

In the conduct of safe refinery practices, it is necessary to make provisions for the handling of flammable vapors which may build up in a system due to a breakdown of equipment. This is done by venting the system at desirable sites and flaring. Sulfur dioxide may be liberated into the air from the sources. Flaring should be kept at a minimum. Good plant designing, as well as auxiliary equipment, such as additional compressors, will accomplish much in this respect. Improved flare tips might also reduce contamination from this source.

Other less significant sources of atmospheric pollution may add to the over-all load contributed by refineries. There may be a multiplicity of leaks and spills throughout the area from which evaporation can take place. Since many of the processes operate under high temperatures and pressures, oil mists also may often be seen around leaky distillation equipment. The best control against atmospheric contamination from such sources is to keep the equipment in good condition.

Maintenance and repair shops may likewise give rise to a multiple source of minor contaminants. Spray painting and abrasive blasting operations are but two examples. Standard collecting devices are already available to prevent air pollution from sources such as these and should be used.

Many of the refineries are expanding their operations to include the processing of petroleum chemical products. These are too numerous to be considered here. However, these processes provide a potential source for atmospheric pollution.

## Comment

With the expanded refinery capacity for processing crude oil along with the greatly increased production from cracking processes, the refinery industry must be alert to the increasingly important problem of atmospheric pollution. The industry is already aware of many of the problems with which it is faced. The program of the refining industry in the Los Angeles area is but one example. In this instance the Western Oil and Gas Association is sponsoring an intensive research program through the Stanford Research Institute. Research is under way to uncover the factors which constitute the Los Angeles smog and determine in what ways the petroleum refining industry may be contributing to the problem. This type of research is commendable and should be extended to include a study of more efficient and economical methods and devices for preventing atmospheric pollution. Every refinery should make a complete study of its operations and processes to determine the nature and extent of the contamination it may be contributing to the over-all community atmospheric pollution load. This basic information must be obtained before any intelligent method of control can be instituted.

## References

1. Lott, F. S., and Culver, I. S.: Petroleum Refineries, Including Cracking Plants, in the United States, January 1, 1949. Bureau of Mines Information Circular 7537, September, 1949.

2. Sachanen, A. N.: Conversion of Petroleum, Second Edition. Reinhold, New York, 1948.

3. Ellis, Carleton: The Chemistry of Petroleum Derivatives, Vol. II. Reinhold, New York, 1937.

4. Symposium on Sulfur in Petroleum, presented before the Division of Petroleum Chemistry at the 115th meeting of the American Chemical Society, San Francisco. *Industrial & Engineering Chemistry*, 41:2680-2737, December, 1949.

5. Reed, H., Reau, M. A., and Stribley, A. F.: The Petroleum Industry and Smog. *Petroleum Processing*, 4:391-394, April, 1949.

6. Sulfur from Sour Refinery Gases. *Petroleum Processing*, 4:891-892, August, 1949.

7. The Smog Problem in Los Angeles County. Second Interim Report by Stanford Research Institute on Studies to Determine the Nature and Sources of the Smog, Sponsored by Committee on Smoke and Fumes, Western Oil & Gas Association, Los Angeles, August, 1949.

# Determination Procedures

PAUL L. MAGILL,
Supervisor, Air and Water Pollution Laboratory,
Stanford Research Institute,
Stanford, California

SOME three years ago the Stanford Research Institute was asked to undertake a fundamental investigation of smog in Los Angeles. This request was symptomatic of a growing public and scientific awareness that air pollution actually was and is a problem—an awareness that has sprouted and grown enormously during the past three years. The word "smog" is today a household term, usually loosely used to be sure, but always implying the existence of an impure atmosphere.

Increasing awareness of air pollution problems branches into many fields of science—more, indeed, than one may at first imagine. Events, of course, have given urgency to the scientific approach to the problem. The incident at Donora, the persistence of smog in Los Angeles, the snowballing of complaints of private citizens in an ever-growing list of towns and cities, the vigor with which legal actions are being taken—all have accentuated the seriousness of the problem.

The facets of the scientific approaches to air pollution are numerous, but each approach must in the long run be based upon an accurate knowledge of the impurities in the air. This necessity, of course, leads directly to the subject I wish to discuss—namely, Determination Procedures—and I welcome this opportunity to present some of the results of our experience.

The selection of the proper procedure must be based in each case on the specific requirements of the job, the skill of the operators available, and the equipment at hand. The problem of selecting the proper procedure is not always simple. All too frequently the impurities of the atmosphere make themselves evident only by their effects—such as crop damage, influence on health, or, as occurs in Los Angeles, irritation to the eyes. At the outset it may not be known whether the impurity exists in the form of a gas, as liquid droplets, as solid particles, or as any combinations of the three. In some cases the concentrations may be so low that they are near the threshold of sensitivity for known methods of detection.

I am tempted to say unqualifiedly that the impurities must be collected before they can be determined. However, modern spectrographic and photographic methods invalidate so sweeping a statement. Nevertheless, it is of great assistance in the determination of atmospheric impurities to be able to collect enough of the pollutants to analyze them by more conventional means.

With these general problems and limitations in mind, I should like to discuss first the collection and analysis of particulate matter, then the determination of gaseuos impurities, mention a few points pertinent to the application of these methods, and finally outline a few of the many unsolved problems in determination procedures.

## Particulate Matter

COLLECTION: It is the particulate matter in the atmosphere that causes the reduction of visibility and the formation of visible smokes and hazes. To specify equipment for cleaning gases it is first necessary to know the particle size distribution, the quantities, and preferably the composition of the contaminating matter. If the properties of the atmospheric pollutants are known, it is frequently possible to name their sources even after the pollutants have become well mixed in the open atmosphere.

To obtain large quantities of particulate matter for chemical analysis a household-type Westinghouse Precipitron has been most useful. Although the equipment is movable it cannot properly be called portable. With such a unit it is possible to remove the particulate matter from air at a rate of air passage of approximately 1200 cfm. The device may be turned on and off with a time switch if it is desirable to collect materials over only specific intervals of time. Depending upon the degree of contamination of the atmosphere it is possible to collect 10-20 grams of material by means of the Precipitron during a period of operation of two to three days. The instrument

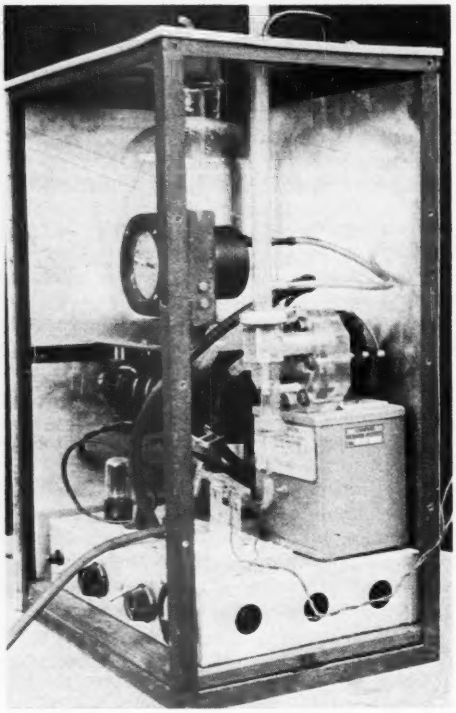


Fig. 1.
Wet-type electrostatic precipitator

is not readily adaptable to estimating the day-to-day or hour-to-hour changes in atmospheric pollution. On the other hand, it serves to provide an average sample of particulate matter that is representative for the period of operation. Samples collected are frequently mixtures of liquids and solids and are not readily redispersed for particle size examination. A small quantity, 5 to 10 milligrams, of such material is ample to obtain rather complete analysis by micro-analytical and emission spectrographic methods.

Where portability is important small electrostatic precipitators may be used. Such precipitators may be either purchased or constructed. We preferred an instrument of our own assembly that was so designed that it collected samples on a single flat plate the size of a microscope slide (Fig. 1). This instrument was provided with means for accurate voltage and air flow controls. It was especially useful in collecting sulphate particles from the atmosphere which were later determined quantitatively by turbidimetric methods.

A variation of this instrument adapted for continuous readings was constructed in such a manner that the collecting electrode was a rotating stainless steel plate partially immersed in a liquid bath. This instrument is useful for the colelction of sulfuric acid mist from the air. The mist is collected on the rotating plate and is washed off during the rotation in the bath, which may be either conductivity water or dilute sulfuric acid. The washing solution flows from the electrode compartment through a conductivity cell where its conductivity is continuously recorded. The solution that flows out of the conductivity cell may be saved and analyzed for specific impurities.

A Sonkin cascade impactor[5] is useful for collecting samples over short periods of time and for following moment-by-moment changes in atmospheric pollution. This impactor, which causes the air to pass through a series of narrowing jets, collects particles by impingement on glass plates and yields a rough classification of particles according to size. If the sample collected is not too large the particles arrange themselves on the slides in such a manner that they can be measured in size and examined for composition under a microscope. Although the Sonkin cascade impactor collects some particles less than one micron in diameter if the velocity through the last jet approaches that of the speed of sound, it is not particularly efficient for collecting these small particles—it is less efficient, for example, than the thermal precipitator. This difference in efficiency of collection is graphically illustrated by the results from a typical comparative test made during a light smog haze in Los Angeles. One hundred cubic centimeters of air were passed through the thermal precipitator and approximately 75 cc. of air through the impactor. A particle count gave 130 million particles per cubic foot for the thermal precipitator. The total count for the impactor yielded 30 million particles per cubic foot, or a ratio of approximately four to one in favor of the collection efficiency of the thermal precipitator. Particle sizes were counted down to approximately 0.2 micron in diameter.

The principle of operation of the thermal precipitator was pointed out by John Aitken

about 1870.[3] It collects particles by taking advantage of the particle-free atmosphere that surrounds a hot surface. By passing air between a heated wire and adjacent glass plates it is possible to collect on the plates the fine material that is repelled from the wire. The thermal precipitator is advantageous in that it appears to collect all fine particles; however, it must be operated at very low air flow rates. The rate of air passage can be increased by substituting a flat ribbon for the wire. This has the further advantage of simplifying the problem of selecting the proper flow of air. When the width of the deposit of the particles on the glass plates is less than the width of the heated ribbon it is almost certain that all the particles are being collected; on the other hand, if the width of the deposit is greater than that of the ribbon the air flow rate probably is too rapid and some of the particles are being lost. This device is well adapted for collecting particles on coated screens for subsequent examination with the electron microscope.

In making particle counts it must be remembered that there is always some limiting factor to the number of particles that can be counted by the observer. A limitation may arise from the device used for observing the particles. Thus, for example, it is not easy to obtain the same distribution curves for particles with the electron microscope as with the optical microscope (in the ranges where the two overlap). Sometimes the limiting factor is the collection device or the sampling technique. Where it is necessary to state with certainty the absolute number of particles of a given size range in an atmosphere, great care must be exercised and cross checks obtained by independent means. In our work it was finally possible, by improving the technique, to obtain particle counts that accounted for the loss of visibility in the Los Angeles atmosphere as arrived at from the optical theory of scattering and the measurement of the attenuation coefficient by photographing the haze in the open atmosphere.

Sulfur trioxide in the atmosphere, generally in the form of sulfuric acid droplets, is one of the most common contaminants. For collecting these droplets, which are notoriously elusive, both the electrostatic precipitator and a modified Venturi scrubber have proved useful.

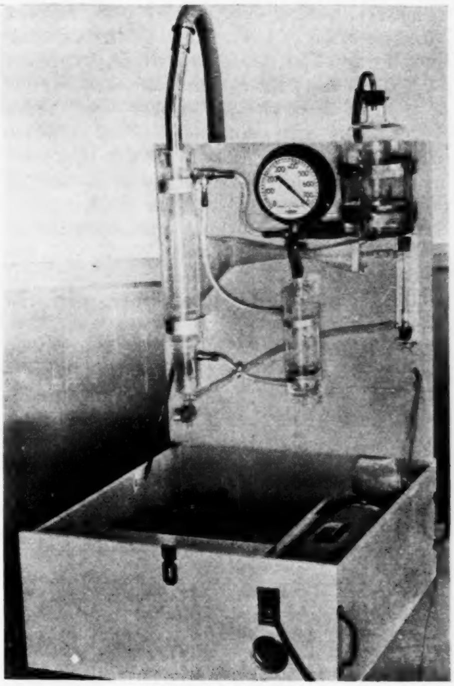


Fig. 2.
Portable Venturi scrubber

The modified Venturi scrubber (Fig. 2) offers the marked advantage of collecting in a relatively short time sufficient material from the atmosphere to permit a gravimetric analysis by a laboratory staff trained in simple analytical techniques. With this equipment it is possible to scrub approximately 10,000 cubic feet of air in six hours and to concentrate the collected matter into approximately 150 cc. of water. The instrument is also useful for collecting other materials such as fly ash, soot, metal oxide particles, and so forth, and is portable enough to be useful in field operations. The collecting solution may be filtered and the insoluble matter analyzed separately for particle size and composition.

The collection of particulate matter by passing air through filter paper frequently offers many advantages. Although it is often difficult to remove the impurities from the paper fibers it is possible in many cases to characterize the substance by carrying out chemical reactions on the paper. This

method has been successfully used for the determination of elemental sulfur in the atmosphere.[4] The paper is first impregnated with thallous sulfate, and the air sample is passed through the paper. The paper is then dipped in dilute acid. The presence of sulfur results in a brown color that may be matched colorimetrically against standards. Where the color of the air contaminant is known, for example in the cases of soot or carbon black, the density of the shade on the paper is roughly proportional to the quantity of contaminant, and the amount in the atmosphere may be estimated directly. The quantity of oil droplets may be estimated by collecting them on filter paper, although in this case several papers in series have been found necessary. The oil

TABLE I.
ANALYSIS OF SAMPLE COLLECTED FROM WESTINGHOUSE PRECIPITRON
(Sample Collected February 16—February 23, 1949)

| | | | |
|---|---|---|---|
| Minerals and other inorganic substances about 45% of total | Water-soluble fraction about 15%; Water-insoluble fraction about 30% | Elements identified by emission spectrograph: | |
| | | Large Amount 10% + | Calcium* Aluminum* Silicon* |
| | | Small Amount 1—9% | Sodium Magnesium Titanium Lead Iron |
| | | Very Small Amount 0.1—0.9% | Copper Manganese Nickel Zinc |
| | | Trace 0.001—0.1% | Lithium Barium Strontium Silver Boron Vanadium Tin Chromium |
| | | Substances identified by chemical analysis: | |
| | | Sulfates as $H_2SO_4$ | 5.7% |
| | | Ammonia | 1.5% |
| Organic Compounds, soluble in benzene or petroleum ether about 16% | | Mainly aliphatic hydrocarbons | |
| | | Also small amounts of aldehydes and organic acids | |
| | | Peroxides, 0.15% calculated as hydrogen peroxide | |
| Fibers, pollen, carbon, and highly polymerized organic material about 15% | | Water and volatile organic substances (by difference) about 24% | |

*Probably from minerals

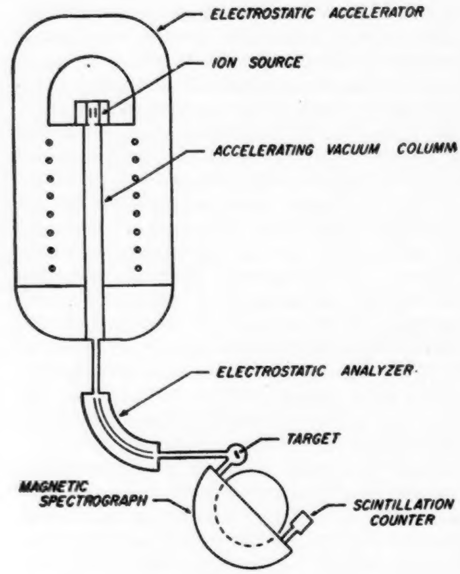



Fig. 3.
Proton scattering apparatus

is removed by leaching the paper in a volatile solvent which is later volatilized, leaving a residue that may be weighed. Fluorides in solid form in the atmosphere can be conveniently collected on filter paper and analyzed by the Willard and Winter method.[8] Whatman No. 32 filter paper has been found to be especially satisfactory for this purpose because of its low fluoride content.

ANALYSIS: The very act of collecting and concentrating particulate matter from the atmosphere may result in chemical changes in the materials. When the impurities are present in concentrations of only a few or perhaps fractions of a part per million it is clearly possible for reactive materials to coexist in forms which do not persist after they have been concentrated. For this reason any analysis of the material after collection must be interpreted in terms of its original environment. This difficulty is for the most part inescapable, but it underlines the importance of making extremely accurate analyses, in order that the most accurate inferences may be drawn.

The micro-analytical methods, the emission spectograph, and the ultra-violet and

infrared spectrometers are all useful analytical tools. Table I shows the results of an analysis, by means of microanalytical methods and the spark emission spectrograph, of material collected from an electrostatic precipitator in Los Angeles during a period of smog. The use of the petrographic microscope frequently provides many short cuts.

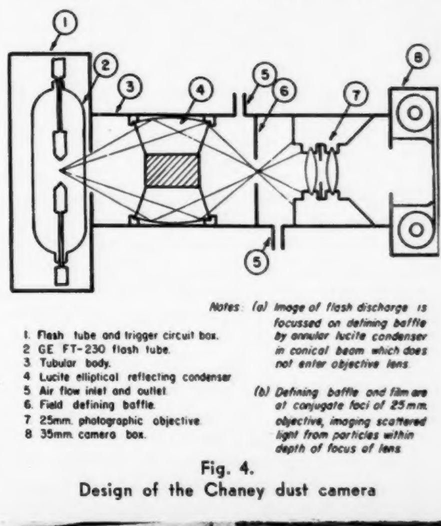
The chemical identification of exceedingly small quantities of materials has recently been supplemented by the development of the proton scattering method (Fig. 3). This is a new tool that provides a quantitative analysis of samples that may weigh considerably less than a millionth of a gram.

In brief, the method involves exposing in a vacuum a sample only a few molecules thick, collected on an aluminum or beryllium foil, to a bombardment of positive hydrogen ions (protons). When the protons strike the sample of material being analyzed, they are bounced off at various velocities, depending upon the weight of the individual atoms contained in the sample. By measuring the velocities of the protons that have rebounded, it is possible to determine the exact element they have struck. Although only a few tests have been made with this instrument, it has been possible to identify in the Los Angeles atmosphere the presence of lead, zinc, and sulfuric acid. This instrument was built in the Kellogg Radiation Laboratory at the California Institute of Technology and its adaptation to the smog problem was developed by Dr. Sylvan Rubin, of Stanford Research Institute, in cooperation with Mr. Volney Rasmussen and Dr. C. C. Lauritzen, at the California Institute of Technology.

The method of analysis recently described by Dr. W. D. Crozier for the identification of particulate matter is a new and useful development. This method involves coating particulate matter collected by the impactor method with a thin layer of collodion; a reagent is then placed on top of the collodion and permitted to diffuse through to the materials to be identified. This provides a valuable means of preserving samples as well as carrying out reactions with individual particles.

**OPTICAL AND PHOTOGRAPHIC MEASUREMENTS:** We frequently wish to know how the particles existed in the free atmosphere before they were modified in physical form by collection. For this purpose direct photographs of the light scattered by individual particles suspended in air are useful. A dust camera designed and built by the Chaney Laboratories in Los Angeles has been used for this purpose in our work. This camera took photographs of the particles in their natural state in the air. Actually the photograph records only the bright light that is scattered by the individual particles. By knowing the focal length of the camera and, consequently, the volume of space photographed, this apparatus makes it possible to count the number of particles per unit volume, although it is not as yet adapted to measuring particle size (Fig. 4).

An approximation of the particle sizes of




1. Flash tube and trigger circuit box.
2. GE FT-230 flash tube.
3. Tubular body.
4. Lucite elliptical reflecting condenser
5. Air flow inlet and outlet
6. Field defining baffle.
7. 25mm. photographic objective
8. 35mm. camera box.

Notes: *(a) Image of flash discharge is focussed on defining baffle by annular lucite condenser in conical beam which does not enter objective lens.*

*(b) Defining baffle and film are at conjugate foci of 25mm. objective, imaging scattered light from particles within depth of focus of lens.*

Fig. 4.
Design of the Chaney dust camera

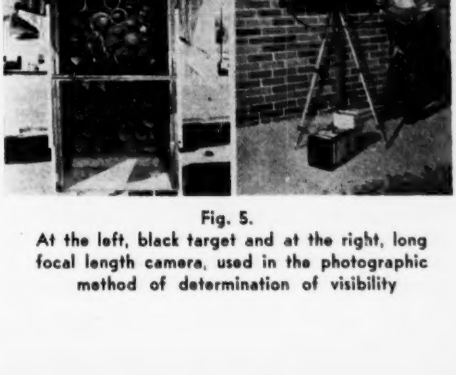


Fig. 5.
At the left, black target and at the right, long focal length camera, used in the photographic method of determination of visibility

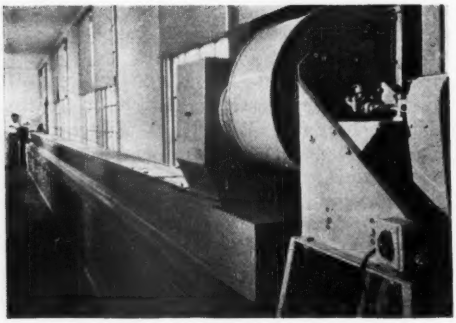


Fig. 6.
Transmissometer

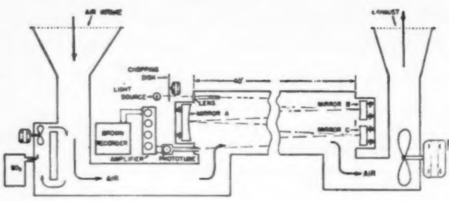



Fig. 7.

Schematic arrangement of transmissometer

impurities in the atmospher can be obtained by the method described by Steffens. This technique involves the photography of black objects in the open air through colored filters (Fig. 5), thus permitting the attenuation coefficient of the atmosphere to be measured for different colors of light. By this means it was determined that the average particle size during smog periods in Los Angeles was of the order of 0.3 to 0.4 micron. The photographs, of course, also provide a permanent record of the visibility.[6,7]

Still another instrumental means of measuring the properties of the atmosphere without collection is the transmissometer (Figs. 6 and 7). A laboratory instrument used for this purpose was built in such a manner that light could be passed through a 40-foot column of air one or more times. The opacity of the air in the column was measured by instrumental means, the scale reading being directly proportional to the intensity of the light passing through the air column. Color filters may also be used with this equipment to obtain relative intensities at different wave lengths of light. Although the instrument shown was designed for use indoors, it may be used outdoors as well by using a single reflecting mirror. It is sufficiently sensitive that a full scale reading may be obtained from a reflected light traveling over a light path of approximately one mile. At this distance, however, the change in the refractive index of light due to heat waves and difference in moisture content causes disturbing fluctuations. At distances of 200-300 feet these disturbances are not severe. The transmissometer is believed to be well adapted to the constant recording of the dust or fume content in a room or building.

## Determination of Gases

MANY of the common gaseous pollutants can be determined with the aid of equipment such as is shown in Fig. 8. For example:

*Ammonia* is collected by passing 50 cubic feet of the atmosphere through a single scrubber. The scrubber contains known volumes of 0.1 normal sulfuric acid. The ammonia content is determined colorimetrically with Nessler's reagent, using a Lumetron model 402-E colorimeter equipped with an M-440 color filter. This method will measure 0.01 ppm by volume with an accuracy of 10%.

*Aldehydes* are collected by scrubbing 50 cubic feet of the atmosphere with a scrub-

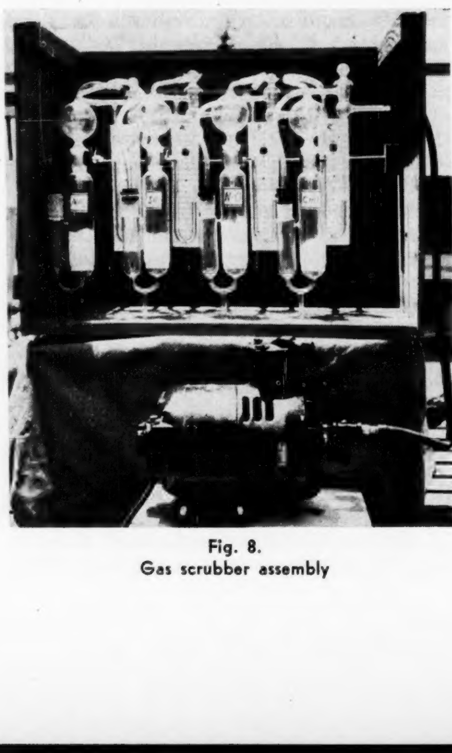


Fig. 8.
Gas scrubber assembly

ber containing 05 ml. of 1% sodium bisulfite. The amount of aldehyde in the solution is determined by a double titration with iodine solution: one titration before decomposition of the sulfur dioxide-aldehyde complex to remove excess bisulfite, and one after decomposition of the bisulfite-aldehyde complex by means of a buffer solution. This method will measure 0.01 ppm aldehyde radical by weight with an accuracy of 50%.

*Sulfur* dioxide is collected by scrubbing 50 cubic feet of air with an absorber containing 50 ml. of 0.1 normal sodium hydroxide. The solution is cooled and 4 volume per cent of benzyl alcohol added to minimize oxidation of sulfur dioxide. The concentration of sulfur dioxide is found by use of the sensitive chromogenic reaction of sulfur dioxide, fuchsin, and formaldehyde in acid, described by Grant.[2] Color intensity is measured using a photoelectric colorimeter (Lumetron) equipped with a green filter. This method will measure 0.2 ppm with an accuracy of 20%.

*Nitrogen oxides* are collected by scrubbing 50 cubic feet of air in a scrubber containing 50 ml. of a 5% sodium hydroxide solution. The nitrogen oxides in solution are oxidized to nitric acid with hydrogen peroxide. The amount of nitric acid is then estimated colorimetrically by using phenoldisulfonic acid reagent. This method will measure 0.05 ppm with an accuracy of 10%.

The possibility of interference between some of these materials must be taken into account. For example, the presence of aldehydes in sufficient quantities will interfere with the accurate analysis of ammonia. Or, again, the sulfur dioxide results may not be accurate if there are large quantities of ozone or other active oxidizing agents in the air.

Organic compounds in the atmosphere can frequently be measured by replacing the aqueous solutions in one of the bubblers with dodecane and measuring the infrared absorption spectra.

Some materials can best be measured by freezing them out of the atmosphere with liquid nitrogen. The apparatus suggested is shown in Figs. 9 and 10.

In the freeze-out train the air is passed successively through three traps, the first and second kept at $-80°C$, and the third at $-195°C$. Gaseous impurities are condensed on the walls of these flasks. In most operations some of the oxygen in the air is also liquefied. After a quantity of the atmosphere—usually about 300 cubic feet—has passed through the apparatus, the flasks are removed and allowed to warm slowly. The characteristics of the residue are carefully noted and analyzed.

Fig. 9.
Freeze-out train

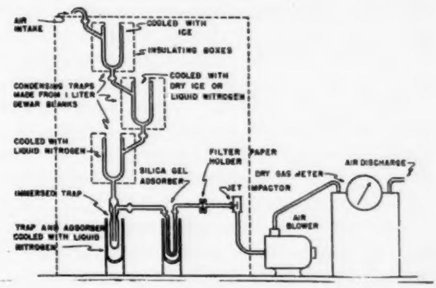



Fig. 10.
Freeze-out train and auxiliary equipment

For the detection and estimation of gases that are physiologically active with respect to plant life, the Epinasty test described by Rohrbaugh should not be overlooked. This method is based on the change in the direction of growth of pea shoots when exposed to some gases. This method, for example, may be used to determine semi-quantitatively concentrations of ethylene as low as 0.25 ppm by volume.

## Application to Practical Problems

IN THE practical applications of the methods described previously the importance of sampling cannot be emphasized too strongly, and every sampling situation creates a new problem. In the space available it is only possible to generalize and mention a few practical illustrations.

The accurate measurement of the sulfur trioxide content of a gas stream is frequently quite difficult.

A laboratory scrubber such as a bottle filled with glass beads or an absorption tower that might collect over 99% of a soluble gas is likely to collect only 2 to 10% of the sulfur trioxide fumes. Depending upon the end results desired, collection by the electrostatic precipitor, the Venturi scrubber or on filter paper is recommended. When the concentrations are low and the gas stream is hot there are several precautions to be observed. All lines through which the sample is taken to the sampling apparatus must be kept hot to avoid condensation of moisture and loss of sulfur trioxide to the walls. The lines should be glass throughout and the gas should be cooled and humidified before it enters the analytical collection device. If collection of the sulfur trioxide is attempted before the particles are allowed to grow by humidification, serious losses may be encountered.

Two common oversights in sampling particulate matter (of especial importance if the particles measure 10 microns or larger in diameter), are failure to be certain that the inlet tube from the main gas stream to the sampling device is pointed upstream with respect to the gas flow, and not adjusting the gas velocity at the entrance to the sampling tube to approximately that of the gas in the main stream carrying the particles. This second difficulty usually can be overcome by adjusting the size of the inlet of the sampling tube properly with respect to the rate of withdrawal of the sample. If this precaution is not observed there may not be the same particle size distribution in the sample as in the main gas stream being analyzed.

In general the simplest method that gives the desired results is the one to be used in each case. By way of illustration, let us assume that we have a black smoke stream entering a cleaning device, and the bulk of the smoke particles are above 2 microns in diameter. We merely wish to know the efficiency of the cleaning device. A satisfactory procedure would be to collect a sample of the smoke particles on white filter paper until some arbitrary gray shade of smoke contamination was visible. This could be done merely by drawing air through the filter paper at a known rate for a known length of time. The same procedure and sampling rates should be employed in collecting the smoke at the discharge of the air-cleaning equipment, but in this case it would presumably be necessary to operate the sampling device for a longer period in order to attain a smoke stain on the paper of the same color intensity as that at the inlet. Let us say that it took 100 minutes' operation at the discharge to obtain the same arbitrary color as that left on the paper at the inlet in 10 minutes. The efficiency of the cleaning device would then be approximately 90%. This procedure gives only an approximation of the efficiency, but for many purposes it would probably be good enough. On the other hand, suppose that this black smoke is highly toxic and the absolute amount of the material leaving the cleaning device must be known as well as the particle size distribution. To gain this information involves all the best sampling techniques and equipment that can be commanded. The final particle size counts would have to be based on the result of a statistical sampling procedure. The electron microscope would have to be employed to count the particles, since the toxic effect of particles in the size range below those observable with the optical microscope must be taken into consideration.

In determining small quantities of odoriferous materials the results obtainable by a skilled microanalyst should not be overlooked. As an illustration of what can be done, it may be recalled that Dr. Haagen-Smit at the California Institute of Technology not only recovered but isolated and determined the composition of the perfume evolved from a single rose. This was done by condensing the volatile components from the atmosphere with a system similar to that previously described and working with a milligram or so of the recovered perfume.

## Some Unsolved Problems

THERE are numerous kinds of problems that beset the analyst and investigator

in the field of air pollution, not the least of which is the availability of adequate equipment. Air pollution problems may arise suddenly, and the need for equipment is great when the occasion arises. I do not know of any manufacturers of impacting equipment or thermal precipitators in this country.

Continuous automatic recording instruments that are specific with respect to what they measure and respond quickly to changes in concentration are extremely useful. They not only replace at lower cost many man-hours of manual sampling, but they frequently provide information that cannot be obtained by hand-operated equipment. The charts from such instruments can frequently be correlated with changes in wind direction, atmospheric stability, and changes in emission rates. They also provide a valuable record for reference purposes where legal actions are involved. Many of the present instruments are not specific for the atmospheric impurity that is being investigated. This factor is not important where only one substance of known composition is present as a pollutant, but when the contamination consists of mixtures of complex composition it takes many pieces of equipment, perhaps each operating on a slightly different principle, to arrive at even an inferential answer.

Better equipment and procedures for collecting and concentrating gaseous impurities need to be developed to assist in their identification by the infrared and ultraviolet spectrographic methods.

Many of the existing analytical methods for the determination of gaseous impurities lack sensitivity and are tedious. For example, a more sensitive method for the detection and measurement of chlorohydrocarbons in concentrations less than one part per million is to be desired, and a less tedious method for the determination of fluorides in the air would be welcome.

It may seem strange to many, but it appears that much improvement is still needed in techniques for the easy measurement of the volume of gases being emitted from a particular source. All too frequently it is necessary to make this measurement the hard way by working with pitot tubes and draft gauges close to a hot stack in almost inaccessible parts of factory equipment. Perhaps a photographic method that would show the rate of release of a puff of colored smoke introduced into the equipment might be developed.

These are only a few of the general types of unsolved problems that have come to our attention. Progress, however, has been rapid during the past several years. This is fortunate because, as we all realize, there is still much to be learned about air pollution. Since air pollution is a field with such profound social and industrial implications it deserves our very best efforts.

SUMMARY: The accurate measurement of impurities in an atmosphere is fundamental to any intelligent corrective measures that may be taken to eliminate the pollution. This paper describes some of the methods of determination that have been found to be effective in the investigation of smog in Los Angeles. The collection and analysis of particulate matter and gaseous atmospheric impurities are discussed. The use of the proton scattering technique as a new and useful tool for the analysis of minute samples is briefly described, as well as the direct photographic techniques for estimation of the properties of particulate matter in the open atmosphere. Some of the more common applications of these methods are mentioned, and a few of the many unsolved problems in instrumentation and measurement are outlined.

[ACKNOWLEDGMENT: The work done to date by the Stanford Research Institute on the Los Angeles smog problem has been sponsored by the Committee on Smoke and Fumes of the Western Oil and Gas Association.]

## Citations

1. CROZIER, W. D.: "Some Techniques for Sampling and Identifying Particulate Matter in Air." Paper presented at National Air Pollution Symposium, Pasadena, California, November, 1949.

2. GRANT, W. M.: *Ind. & Eng. Chem. Anal. Ed.*, 19 (5):345-6, May, 1947.

3. KNOTT, C. G.: "Collected Scientific Papers of John Aitken." Cambridge University Press, London, 1923.

4. MAGILL, PAUL L., MYRA V. ROLSTON, and R. W. BREMNER: *Anal. Chem.*, 21 (11):1411-12, November, 1949.

5. SONKIN, L. S.: "A Modified Cascade Impactor." *J. Ind. Hyg. & Toxicol.*, 28:269, 1946.

6. Stanford Research Institute: "The Smog Problem in Los Angeles County." Second Interim Report, 1949.

7. STEFFENS, CARSTEN: "Measurement of Visibility by Photographic Photometry." *Ind. & Eng. Chem.*, 41:2396, 1949.

8. WILLARD and WINTER: *Ind. & Eng. Chem. Anal. Ed.*, 5 (1):7-10, January, 1933.

9. ROHRBAUGH, P. W.: "Measurement of Small Concentrations of Ethylene and Automobile Exhaust and Their Relation to Lemon Storage." *Plant Physiol.*, 18 (1):79-89, January, 1943.

# Pollution and Controls in Industry

K. E. ROBINSON,
Ventilation Engineer, Division of Industrial Health,
State Department of Health,
Lansing, Michigan

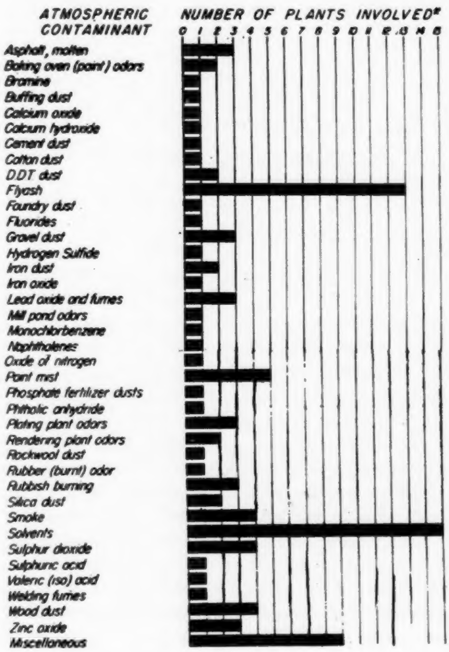
You have heard lectures and discussions mostly on the general principles and theories involved in the control of air contaminants. In my discussion, I am going to stress the other side—the practical application of these principles and theories. A government agency such as ours is in an extremely favorable position to make this type of presentation because we are directly involved with the pollution problem from the time the initial complaint is received to the time when a study is conducted to evaluate the collection equipment installed.

Whether the contaminant be fly ash, alpha-napthoquinone, or odors from a nearby rendering plant or millpond, we are eventually called in to investigate. These investigations can be initiated by the irate housewife who is disturbed by sulphide odors, or the plant manager who maintains that dust from a nearby abrasive reclaiming plant is ruining the bearings in his expensive machinery.

Actual legal authority on these problems rests squarely with local governmental units. In the Michigan Department of Health, we can act in an advisory capacity only. Many of the air pollution cases we are asked to investigate come from local governments who do not have the technicians and the equipment to work on the cases or because the local officials are reluctant to act, fearing that the company will suspend operation in their town. They would rather have the state take the brunt of this burden. In all cases, we make every effort to be of assistance to the local authorities, to the people of the community, and to the industry involved.

The year-to-year increase in the number of requests received for service on air pollution problems, from six in 1940 to nearly a hundred in 1949, indicates the prominence of air pollution in our everyday life. Many of the plants at fault are probably not of sufficient size to afford to spend a great deal of money on contaminant control. Despite the fact that we are not backed by a specific statute and are rarely able to show that the concentrations of the atmospheric contaminants are toxic rather than a serious nuisance, we have found that most industries will consider a practical approach in eliminating the air pollution problem arising from their plant. One of the most successful methods we have of working out a satisfactory solution is to get both the citizens and the management of the industry together. In this manner, management realizes the extent of the nuisance, and the people of the community realize the practical difficulties facing the management in eliminating it.

Investigations by the Michigan Department of Health have turned up a wide variety of contaminants (Fig. 1), and some are very difficult to control. In some in-




*Some plants responsible for several contaminants.

Fig. 1.

stances, a satisfactory method of collection is still to be found, and we welcome any suggestions you may have. There is, of course, no perfect method of collection for any contaminant.

When faced with the problem of collection, there are four things to be considered: first, the selection of the method or collector which is suitable for the job; second, the initial cost of the equipment and installation—and whether this cost is justifiable considering the extent of the nuisance; third, the maintenance on the equipment (a big item with many collectors), and whether it is within an acceptable range or requires frequent expensive replacements and high maintenance costs; and fourth, whether disposal of the collected material is difficult or costly. The following case histories demonstrate that these considerations are extremely important factors in every air pollution problem.

## Case No. 1

AIR pollution problems involving odors are often extremely difficult to cope with. One of the biggest problems is the elimination of odors. Our sense of smell is often an excellent method of chemical analysis; its delicacy is often greater than any chemical analysis we can run in the laboratory. There are many materials which we can smell long before the concentrations are high enough to enable us to run a chemical determination. Since odors may be due to these minute concentrations of gases and particulate matter, they are extremely hard and often almost impossible to eliminate from the air.

Inasmuch as rendering operations are practically a necessity in all good-sized communities, this case will serve to summarize some of the difficulties we have had with them in several of the cities of the state. The complaints concerned obnoxious stenches which permeated the residential areas near the rendering plant. Upon investigation it was observed that the operating techniques in most of the departments were unsatisfactory, and that a good deal of the odor could be eliminated by improved sanitation and work methods. Several recommendations concerning housekeeping and sanitation procedures were made, including the following:

1. That the sanitation and housekeeping be well planned to include all operations. and that one or two individuals be delegated the responsibility of carrying out the program.
2. That an ample supply of steam and hot water be provided for cleaning and rinsing purposes.
3. That the building receive a thorough initial cleaning, and that certain structural changes be made, such as re-surfacing floors with an impervious material.
4. That a central wash station be provided for all containers and a storage space provided for all clean containers.
5. That materials coming into the plant which were not to be used immediately be stored in properly enclosed containers.
6. That a driveway be constructed of impervious material which could be flushed off.

In addition, local exhaust ventilation for certain operations was recommended.

Shortly after our study of the operations, a group of citizens and the city filed a suit asking that an injunction be issued to restrain the company from polluting the atmosphere with offensive odors. In court, the company stated that in an effort to abate the stenches and smells emanating from the plant, they were acting upon our recommendations. In addition to our recommendations, they had installed two modern cookers; a modernized, used cooker; a new septic tank; a condenser water tank; an additional sewer, and an ozone generator. They had enclosed the elevator shaft with steel, entirely segregating it; purchased an additional boiler, and agreed to construct a new driveway. The driveway was to be of concrete or other comparable material, and was to be made non-absorbent. The court found that the nuisance did exist and had existed for a long time, and stated that the plaintiffs were entitled to the relief sought by them. The company was ordered to wholly abate the nuisance within 30 days; with additional time, if necessary, to complete the installation of the new boiler. The complaints of the residents, the legal action taken and the efforts made by the company to eliminate the odors have helped a great deal to minimize the amount of atmospheric pollution taking place.

Since the completion of the previously mentioned work, there have been no further complaints to the court. It is our opinion that the ozone generators mask the

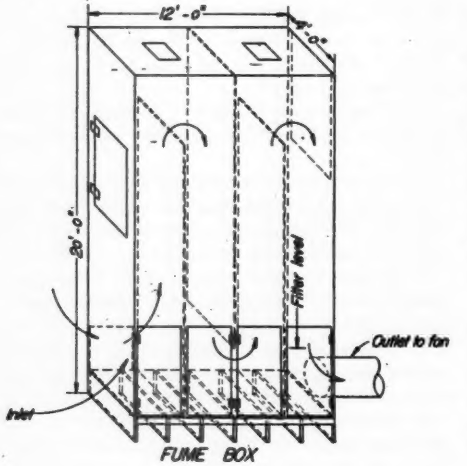



Fig. 2.

is contaminated by a strong pungent odor as well as small quantities of particulate matter. The problem of collecting the annoying stack effluents which are given off by 14 stacks is difficult, and is further hampered by the pyroligenous acids which are produced and can result in explosions and fires. Correspondence with manufacturers of phthalic anhydride and with industrial hygiene units in this country indicates that the same difficulties of collection exist everywhere.

In an attempt to solve these problems, a committee was formed of members of the chemical engineering department of a nearby university, outside engineering consultants, representatives of the company, and several of our engineers. The first attempt to control the contaminant was with the use of steam jets in the tall stacks with the thought that the addition of steam might result in satisfactory collection. It was found that the steam did not help and, in fact, increased the nuisance to the neighborhood. Following this, a standard commercial wet collector was tried and also found unsatisfactory.

While this was being done, the properties of the material were studied and it was found that the contaminant had a tendency to seed and adhere to the ductwork or any other material it contacted. An experimental, box-like duct (Fig. 2) was built. The thought was that a large portion of the material going through the tortuous passage would seed sufficiently and adhere

odors for the plant employees but do not affect the odors emanating from the plant. It is obvious that effective sanitation and housekeeping programs have to be maintained if the odors from rendering plants are to be minimized.

## Case No. 2

Now let us consider a plant producing phthalic anhydride. I have selected this plant because it is a good illustration of practically all the four considerations in selecting a collector which I have outlined.

The plant is large and centrally located in a residential district. The neighborhood

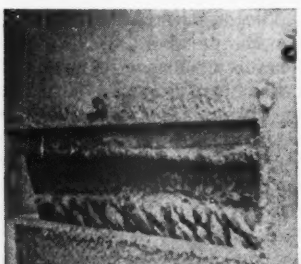


Fig. 3.

Fig. 4.

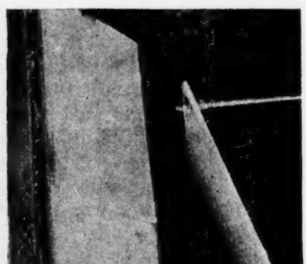


Fig. 5.

to the baffles, thereby minimizing the amount of objectionable material given off. Although large amounts of the material were collected, the odor did not seem to be lessened appreciably. Following this failure at collection, an attempt was made to condense the vapors on a water-cooled, stainless steel wall. However, it was found that the material would not adhere to the wet surface, nor was enough vapor condensed to solve the problem.

A good many things were tried with this box, such as using orifices to increase the velocity in order to impinge the material on a plate. As shown by Figs. 3, 4 and 5, this method removed much of the material but, as previously brought out, did not decrease the odor.

Following months of work on these collectors, a special high pressure fog unit was installed and appeared to work unusually well. However, much water was required and it was found that the water coming from the first section of the collector had a pH of slightly over two and the cost of neutralizing this to allow for disposal was prohibitive.

By this time, sufficient work had been carried on in experimental laboratories to lead us to believe that the strong odor was caused by a by-product, alpha-naphthoquinone, and that concentrations as low as 1 ppm would be objectionable.

Some time after this fog unit was dismantled, the company was approached by two men who had developed a catalyst for burning organic matter from stack effluents. They had had very good success with this catalyst in eliminating odors from wire baking ovens and, judging from previous installations, the system would be reasonably inexpensive to install. Fig. 6 shows the type of system that had been used on the gases from the baking oven. The company decided to try an experimental unit, and a system which might possibly work was designed. Experiments in the laboratory with the catalyst showed that a high temperature would be required. Subsequent work with the unit proved that 400°C was the minimum temperature at which the catalyst would operate. Previous trials had proved that the ducts would clog unless arrangements were made to keep them open, and so a counter-flow system was designed to keep the ducts warm with the thought that the heat from the catalyst would hold the material in the vapor state.

An experimental unit was installed, using a gas flame to increase the air temperature sufficiently for operation of the catalyst. It was found that a good deal of work was

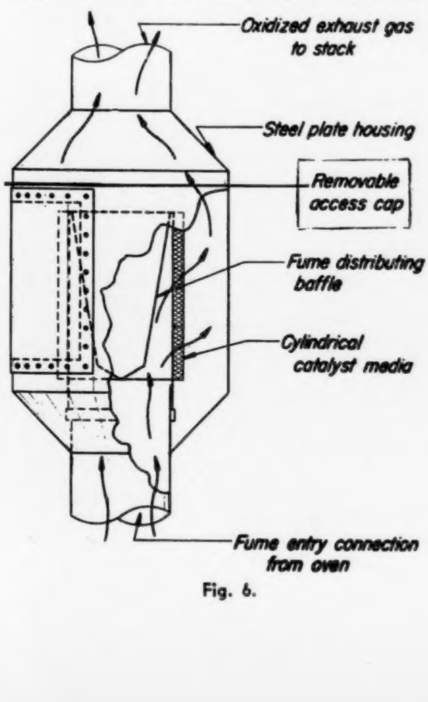



Fig. 6.

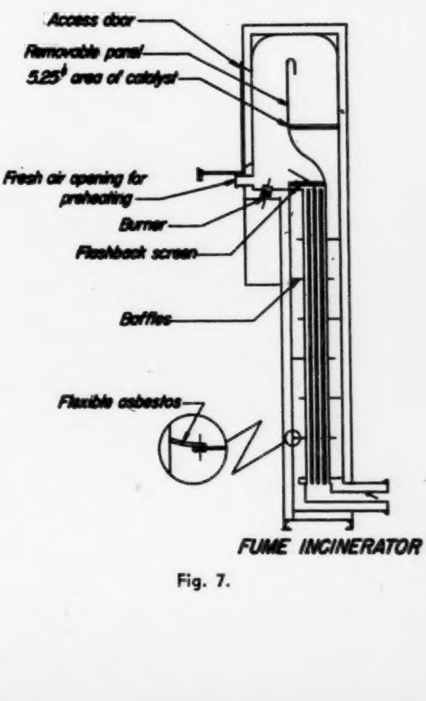



Fig. 7.

necessary to achieve an even temperature and even distribution of air through these catalysts. When this was accomplished and all of the leaks were finally stopped (this was very difficult because of the high experimental temperatures), the system operated quite satisfactorily.

At the present time, work is going forward on the design of a unit which can be installed to control the contaminant from each of the 14 stacks. Fig. 7 gives an idea of the size and complexity of the piece of apparatus to eliminate odors from this plant in comparison to the very simple catalytic arrangement used in another plant with a different material.

Regarding this air pollution problem, I should like to emphasize the desire on the part of the offending company to find a solution of the problem which will be economical and satisfactory to the residents of the community. Practically all reasonable approaches were tried. One method appeared to be satisfactory, but this produced a water pollution problem almost as great as the air pollution problem.

I should also like to bring out here that one of our greatest difficulties results from the fact that it is almost impossible to use a system developed for one operation on another operation in a different plant without many major and often expensive changes.

## Case No. 3

A COMMON atmospheric contaminant is fly ash. Practically every city and village is confronted with this problem. I have selected one fly ash problem from our files because it brings out a point that may be of interest.

The plant is situated in a community of 9000 people and employs about 120 workers. When the plant was built for war purposes the citizens were elated because it gave a big industrial boost to the community. Now there are some citizens who wonder whether their elation was not somewhat premature.

Throughout the war, the plant worked on a round-the-clock basis with no complaints from the people of the community, but after it was taken over by a private company, the local city officials began receiving complaints. The principal complaint was due to fly ash. The people of the community were of the opinion that there had been a collector used when the plant was operated for the government and also that the powerhouse was operated more efficiently and gave off no fly ash.

In making our investigation, we found several reasons for the complaints. One was that the plant had been built along the water's edge to take advantage of dock facilities and, unfortunately, the major part of the city was on a bluff overlooking the plant. Most of the houses of the community are actually higher than the top of the stack of the plant. Like many war plants, this one was designed for a specific operation which utilized the flue gases for a carbonization process. The flue gases required scrubbing which, while consuming a great deal of power, was justified by the fact that the gases would be re-used. In peacetime operations, the carbonization process could not be used and the company could not economically justify the use of such a scrubber. Contrary to the belief of some citizens, the power plant is being operated more efficiently now than ever before. Fly ash collectors are in use, but, like all collectors, they are not 100% effective, and some escaping fly ash settles on the residences nearby.

At the present time, an addition to the stack is being planned and will undoubtedly be built when weather permits. It will be interesting to see whether the addition of this extra height will eliminate the complaints, or will simply deposit the fly ash on residences a little farther out. It appears to us that proper installation of electrostatic precipitation might be more justifiable than a gamble on high stacks for dilution purposes.

## Case No. 4

THE collection of air contaminants in the manufacture of calcium carbide is almost as important a problem as the manufacture of carbide itself. In our investigations into the manufacture of carbide by one large concern, we found that this was a universal problem among the carbide manufacturers. While much work has been done and many engineering organizations have attempted to solve this problem, we believe that contaminant control will not be satisfactory with present collecting devices unless manufacturing procedures are improved.

Calcium carbide is manufactured in the electric furnace by fusing a mixture of lime and coke. The yield from this reaction varies a great deal depending upon the quality of the coal and lime used. The gases and much of the particulate residue from the reaction are removed from the electric furnace by exhaust fans. The particuiate matter taken off from this reaction can run over 100 tons per day. Now if the efficiency of a collector installed to remove this particulate matter from the air runs as high as 96%—and this figure would be high for any collector—it would leave four tons of this material to be thrown into the open air and over the community. If you disperse this four tons of residue into the atmosphere, you can understand that it would do a fairly good job in covering the community in 24 hours. This is the actual problem in controlling air pollution created by a carbide plant. While this air pollution is not a health hazard but a nuisance, it reaches extremely annoying proportions. It is particularly damaging to the painted surfaces of houses and, in some instances, it ruins the finish on automobiles, furniture, etc.

In our work with this particular plant, we collected air samples throughout the plant and in the surrounding neighborhood. The results of the study are shown in Fig. 8. The management, in attempting to alleviate this air pollution, had installed Cottrell precipitators in the stack. The reasons for selecting electrostatic precipitation as a means of collection were: first, experience has shown that electrostatic precipitation, in most cases, works satisfactorily on particulate matter, and, second, the company owned a share of the water rights and produced its own power in that community.

On our investigation, we found that there were several limiting factors in attaining complete success in the collection of the material.

We discovered that the dust-laden flue gases were cooled and moistened by a bank of water sprays before entering the precipitator units. The efficiency of the precipitator varied considerably, owing to the fluctuation in temperature and humidity of the flue gases. Another factor controlling the success of these precipitators was the company's limited water rights. While what power they produced was cheap, production required the greater portion and the remainder was insufficient for constant successful precipitator operation.

DATA SHEET

A. Neighborhood Air Samples

| Location | Dust Count Million Particles Per Cubic Foot of Air | Dust Wt. Mg/10M³ of air | $Ca(OH)_2$ Wt. Mg/10M³ of Air | % $Ca(OH)_2$ in Sample |
|---|---|---|---|---|
| Street No. 1 | 0.326 | 5.5 | 0.74 | 13.4 |
| Street No. 2 | 0.415 | 7.4 | 1.11 | 15.0 |

Dust Analyses

B. Settled Dust in Plant

| | |
|---|---|
| Water | 0.8% |
| Loss on ignition (carbon) | 24.1% |
| Total silica | 1.7% |
| Ca as $Ca(OH)_2$ | 67.1% |
| Fe as FeS | 7.2% |

Dust from Exhaust Stack below Cottrell

| | |
|---|---|
| Water | 1.3% |
| Loss on Ignition (carbon) | 18.3% |
| Total silica | 1.9% |
| Ca as $Ca(OH)_2$ | 69.6% |
| Fe as FeS | 7.7% |

C. Dust Loading of Stack Effluent

| Location | Total Weight Dry Dust Grains per Cubic Foot of Air |
|---|---|
| Cottrell Set No. 1 | |
| Sample No. 1 | 0.093 |
| 2 | 0.102 |
| 3 | 0.055 |
| 4 | 0.107 |
| 5 | 0.029 |
| 6 | 0.161 |
| 7 | 0.122 |
| Average | 0.0956 |

Rated volume = 150,000 CFM

$$\frac{0.0956 \times 150{,}000 \times 60 \times 24}{7{,}000} = 2{,}950 \text{ pounds dust per day from Set No. 1}$$

Note: No data for Set No. 2 but results should be comparable to Cottrell Set No. 1

Fig. 8.
Carbide Chemical Manufacture

We recommended that the company install automatic current and voltage controls; that local exhaust ventilation at the furnaces be improved, and that other collectors be installed between each furnace and the precipitator. But every recommendation requiring an increase in the amount of power used, whether for wet collection or additional electrical precipitation, brought the reply that the power consumption could not be increased at the time and that all available power was necessary to produce an amount of carbide to justify the existence of the plant.

In addition to the various aspects of the problem just mentioned, the fact that the company is the largest single plant in the area, employing about 500 people makes its existence necessary if economic stability is to be maintained in the city. While it might be possible for the residents to take legal action against the company, in view of the important place the industry occupies in the community it is doubtful if such action is wise.

The situation I have just outlined is not unusual. Every collector installation has its limiting factors, and you can determine from the account I have given that these can be extremely perplexing.

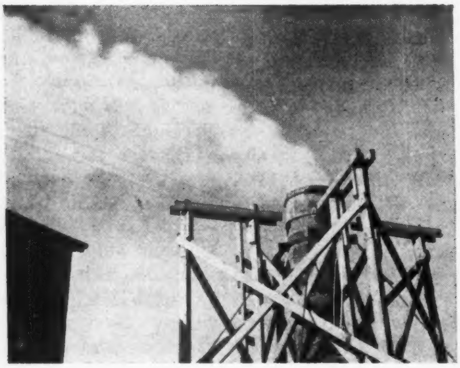


Fig. 9.

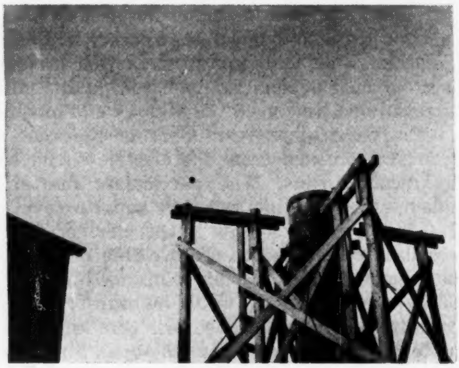


Fig. 10.

## Case No. 5

FROM inquiries we have received from all over the country, the control of air contaminants from chemical fertilizer plants is of interest to many engineers and communities. For that reason, I have selected a chemical fertilizer plant in which I believe we have been quite successful. The usual air contaminant from the phosphate fertilizer plant is due to the dust and vapors given off during the mixing of sulfuric acid with calcium phosphate, resulting in excessive pollution of the atmosphere with phosphate, fluoride and sulphate dust and silicic acid.

The equipment used by the company for controlling the materials given off during the mixing consisted of a wooden paddle type blower which sucked the gases and solid materials from the mixing process up a tall wooden scrubbing tower. Several haphazardly-placed water sprays were used in an attempt to effect water scrubbing and collections of the materials given off.

As a result of our investigation, the company, in attempting to determine what equipment would be suitable for complete collection of the contaminants, had high-pressure fog spray equipment installed and requested that we conduct test runs for determining its effectiveness. The installation was very effective and the results of our tests are shown in Figs. 9 and 10. Visual observance of the stack during operation of the process with the high-pressure fog spray collection equipment both on and off indicated satisfactory collection as shown.

After a period of use during which the fog spray equipment was satisfactory, the company gradually cut down on the water pressure used and finally reached the point where it was considered wise to discontinue the use of a high-pressure pump and install in its place an ordinary pump capable of delivering pressure up to 120 pounds per square inch. No further complaints about the mixing process have been received. However, we recently received complaints concerning a dusty material which was contaminating the neighborhood, and upon investigation we found that a great deal of dust was being liberated by the natural draft ventilators during the mixing of a high nitrate composition fertilizer. It was suggested to the company that bag type collectors be used for collecting this dust. No follow-up investigation has been made, and no additional information is available.

It appeared from our work on this plant that the fog spray method of collection is very well adapted for fertilizer plants of this type, providing, of course, the effluent can be satisfactorily disposed of. Another fertilizer plant which has been constructed since, with fog filters installed, has proved satisfactory.

## Case No. 6

THE next case is that of a manufacturer of asphaltic base sound-deadening coatings. The contaminant involved is once again odors. The plant is located in a city of approximately 2400, and employs about 85 people. Neighborhood residents complained of the foul-smelling stack effluent given off during the processing of flux oils. The process, known in the trade as "blowing asphalt," consists of blowing air

through molten asphaltic flux oil which is maintained at a temperature of about 500°F.

During the process, certain volatile compounds are formed and the lighter portions of the flux oil itself may be distilled off, owing to the elevated temperature.

Requests for information concerning control of the "blowing" process were answered by two large oil companies who supply the company in question with their flux oils. One suggested the use of an electrostatic precipitator or "routing the vapors through a furnace where all hydrocarbon particles are burned, giving off a normal stack gas." The other suggested condensing the vapors into a liquid or washing them with water "by which means the greater part of the more volatile portions are knocked down in the form of a liquid." A third inquiry to the author of an article on petroleum base protective coatings brought the reply that he knew of no completely successful method of controlling the stack effluent but thought that it could be successfully collected if passed through "at least two stages of water spray."

The company did not believe that it could consider the costly electrostatic precipitator installation and, because of the highly inflammable nature of the process, ruled out furnace burning of the stack gases. At our suggestion it was decided to try a high-pressure water spray process, and a nearby manufacturer provided the company with a pilot model so that test runs could be made. Although it could easily be seen from the draining water effluent that much oily type material was being collected, the fog spray process did not completely eliminate the foul-smelling white smoky material which went through the collector and out of the stacks. Fig. 11 is a data sheet covering our fog spray test findings. Although additional test runs with a larger capacity water spray unit might have proved more effective, no further work has been carried out.

The problem of collecting the contaminant remains unsolved, but the company plans to continue the search for a suitable collection apparatus and has informed the city council that it will shut down the blowing operations whenever the prevailing winds result in contamination of the neighborhood.

DATA SHEET

A. Fog Spray Collection of Effluent from Flux Oil Blowing Process

1. Supplementary data

Run No. 1 30 nozzles on, full air flow

Run No. 2 12 nozzles on, cut-down air flow

Run No. 3 30 nozzles on, cut-down air flow

| Run No. | Pump Pressure (Lb. per sq. inch) | Flux Oil Tank Temp. (°F) | Water Flow Rate Gal./Min. | Collector Inlet Temp. (°F) | Collector Outlet Temp. (°F) | Airflow Inlet (cfm) | Airflow Outlet (cfm) |
|---|---|---|---|---|---|---|---|
| 1 | 440 | 520 | 21.6 | 490 | 230 | 700 | [illegible] |
| 2 | 450 | 520 | 10.0 | 458 | 90 | 245 | 212 |
| 3 | 450 | 500 | 21.4 | — | — | 245 | 212 |

2. Collection Efficiencies

| Run No. | pH | | Material Collected | | Efficiency of Collection (%) |
|---|---|---|---|---|---|
| | Inlet | Outlet | Inlet (Grams per cu. ft.) | Outlet (Grams Per cu. ft.) | |
| 1 | slightly acid | — | 0.49 | — | — |
| 1A | slightly acid | neutral | 1.36 | 0.17 | [illegible] |
| 1B | slightly acid | neutral | 1.18 | 0.17 | 86 |
| 2A | slightly acid | neutral | 0.94 | 0.15 | 84 |
| 3A | slightly acid | slightly acid | [illegible] | [illegible] | [illegible] |
| 3B | slightly acid | slightly acid | 1.09 | [illegible] | 87 |

Fig. 11.
Asphaltic Base Coatings

## Case No. 7

WE WERE requested by a city health department to investigate numerous complaints concerning hydrogen sulphide odors. Stack samples collected during the mixing of sulphur with hot purified lard oil indicated high concentrations of hydrogen sulphide.

The gases emanating from the mixing process were passed through beds of limestone and water in an attempt to collect the hydrogen sulphide. Our study indicated that the collection procedure was ineffective. Knowing of no process which would successfully eliminate the hydrogen sulphide, the company had installed a high-pressure fog spray collection unit so that test runs could be made. The results of our study on this unit are shown in Fig. 12. Ordinary water was used as the spray medium, and the collection of the hydrogen sulphide was unsuccessful.

In an effort to decrease the amount of hydrogen sulphide given off, the company decreased the reaction temperature and increased the reaction time. No follow-up study has been conducted since this modification of the manufacturing process, but we plan to evaluate the new procedure as soon as possible.

At the time of the test runs using the fog spray collector, it was suggested that an alkali solution in place of plain water also be

DATA SHEET

A. Fog spray installation for collecting mixing tank effluent gases

1. $H_2S$ concentrations (Inlet and Outlet)

| Sample No. | $H_2S$ Concentrations (milligrams per cubic foot) | | Collection Efficiency (%) |
|---|---|---|---|
| | Inlet | Outlet | |
| 1 | 186 | 140 | 24.8 |
| 2 | 490 | 415 | 15.3 |
| 3 | 800 | 775 | 3.1 |

2. Air movement data

| | Inlet | Outlet |
|---|---|---|
| Duct diameter (inches) | 6 | 7 |
| Duct area (square feet) | 0.196 | 0.267 |
| Air velocity (feet per minute) | 2865 | 2110 |
| Air volume (cubic feet per minute) | 562 | 563 |

*. Note: Collecting medium: water

Fig. 12.
Oil and Grease Company

used for testing purposes, but such a run was not made.

## Case No. 8

COMPLAINTS were received from citizens living near a chemical company engaged in the manufacture of pharmaceuticals. During part of the processing, atmospheric pollution with bromine took place and caused disturbance throughout the neighborhood. The complaint was investigated and it was learned that the pollution disturbance resulted during the warm weather months only.

In order to eliminate the annoyance, the company agreed to compound the materials involving the use of bromine during the winter months. No further complaints have been received.

## Case No. 9

COMPLAINTS were received from the people residing near a small chemical plant engaged in the manufacture of iso-valeric acid. It was learned that the company was considering a new location but its capital was limited. Unable to relocate because of lack of funds, the company was forced to abandon the contract for the manufacture of iso-valeric acid.

## Conclusion

WE BELIEVE these case histories may serve to bring out the importance of the four considerations previously mentioned; namely, the selection of a suitable method or collector, cost of the equipment and installation, maintenance of the equipment, and disposal of the collected material. They also show that there is no cut-and-dried method of controlling the contaminants involved in the term air pollution. At the present time it is our belief that, in many cases similar to the phthalic plant mentioned, even the plant operators do not know what their problem is. We hear a good deal about smoke and fly ash elimination, possibly because we know more about how to eliminate them than most of the other contaminants found. Obviously, the lack of knowledge is the biggest handicap in the control of odors.

# Washers for Particulate Matter Collection

ALLEN D. BRANDT, Sc.D.,
Bethlehem Steel Company,
Bethlehem, Pennsylvania

THE NUMBER of different types of washers or wet collectors available commercially is large and growing rapidly. To discuss them all in the time allotted is impossible. The problem is complicated even more by the fact that there are literally hundreds of home-made washers in use in industry today and hundreds more that are "improved" or otherwise altered designs of commercial models. The obvious procedure is to discuss the important principles involved in particulate matter removal and to show in a general way how these are applied in some of the common commercial wet collectors.

THERE are few problems in engineering that offer a wider range of conditions to be met or overcome than the removal of particulate matter—dusts, fumes, mists and smokes, from air or gas streams. Yet, for obvious reasons, air cleaning problems have not received the attention they probably deserve with the result that today we appear to be on the threshold of an era which will see much activity in air and gas cleaning, i.e., air pollution control, and we are unprepared for it. In air cleaning, as in anything else, one can't get something for nothing; energy must be expended to remove the particulate matter. The more difficult the cleaning operation, the greater the amount of energy that must be expended to accomplish it. Hence, other things being equal, the energy required to remove particulate matter increases as the particle size decreases and as the degree of cleanliness obtained increases. Nevertheless, I feel that with the highly developed state of technology prevailing in this country it must be possible to develop particulate matter collectors which will cost only a fraction of current figures to install and operate. Industry everywhere is making this challenge known to all people engaged in the removal of pollutants from air and gas streams because the capital expenditure required to do the job of air pollution control that industry wants to do is prohibitive at present.[1,2]

Washers or wet collectors are only one of several types of air and gas cleaners. They are used very widely in industry since they possess inherent advantages for certain cleaning operations. Conversely they are not best suited for all jobs because they have distinct disadvantages under certain conditions. It is probably needless to point out that the discussion in this paper will be restricted to wet collectors used for cleaning highly contaminated air as differentiated from wet-type air cleaners that are used so widely to clean the air supplied to occupied spaces for strictly ventilation or air-conditioning purposes.

No attempt will be made to review the history of wet collectors. The rain falling through the atmosphere undoubtedly was the first form of wet washer and may well have been the motivating force in man's activity along this line. Wet methods of removing contaminants from air and gas streams are not of recent origin. Their use for industrial hygiene purposes, i.e., cleaning air exhausted by process ventilating or local exhaust systems, is more recent than for cleaning process gases. For example, wet collectors of various and sundry sort for many years have played and are continuing to play a primary role in cleaning blast furnace gas in the steel industry. The quantity of gas cleaned is huge by industrial hygiene standards, being more than half of the total amount produced which currently is about 12.8 million cfm.

There are five important principles of removal that are employed singly or in combination in wet collectors. What part one principle plays and what another in some collectors is difficult to assess. It is probably only of academic interest, the important question being what is the combined effect. The collecting principles are (1) collision (washing or sweeping of particulate matter from the air stream), (2) centrifugal force or sudden directional change, (3) electrostatic attraction, (4) moisture condensation, and (5) diffusion. Of these (1) and (2) are the most important by far in conventional wet collectors. Diffusion is

probably very important when dealing with very fine particles, in the order of 0.5 microns and less. Since this principle was discussed by a previous speaker and since it applies only to very small particles it will not be expounded in this paper. Moisture condensation, likewise, plays a relatively minor role in common wet collectors and will not be discussed further. Electrostatic attraction probably is not a very important factor in wet collector operation. The important principles are collision and direction change. The fundamentals having to do with electrostatic attraction and with centrifugal force and sudden direction changes were covered completely in previous papers and will not be developed here although the application of the principles of centrifugal force and direction change will be referred to later. It is apparent, then, that the only principle to be developed in this discussion is that of collision.

THERE are many people, including plant engineers, who think that dirty air streams can be washed essentially free of particulate matter by merely passing them through spray curtains. Nothing can be farther from the truth, and much of the money spent installing spray nozzles in stacks, ducts, chambers and cyclones has been rather unproductive. I do not mean to imply that wet collectors are not or cannot be good collectors; some are. But the simple act of passing a dirty air stream through one or several spray curtains does not rid it of particulate matter.

This comes as no surprise to those who have taken a few minutes to analyze what actually happens when water is sprayed into an air stream or when air or gas is bubbled through water. Let us consider, for example, what takes place in a simple type spray washer somewhat similar to that shown in Fig. 1. To simplify the analysis as far as possible and to include in our consideration only the washing effect, let us assume that the air in rinsing through the spray chamber is either not rotating at all or not enough to throw the particulate matter to the walls of the chamber by centrifugal force. Other assumptions are that the drops from the sprays are not too large in relation to the dust particles to be effective in removing them and that the droplets formed by the sprays traverse the entire distance from the axial spray manifold to the walls of the scrubber. Under these conditions, the volume of air swept and, supposedly cleaned, by each droplet takes the shape of a tube, the diameter of which is that of the water droplet and the length of which is approximately the radius of the scrubber. This volume is $\pi d^2R/4$, where "d" is the diameter of the droplet and "R" is the radius of the scrubber. The volume of air swept by the total quantity of water is the sum of the volumes swept by all the water drops introduced by the spray system. Since the volume of each droplet is $\pi d^3/6$, the total number of droplets of "d" size formed by "W" volume of water, is $6W/\pi d^3$. It follows that the total quantity "Q" of air swept by "W" volume of water is $(\pi d^2R/4)(6W/\pi d^3)$ or $1.5\ RW/d$. The percentage of the gas swept by the total water spray into the scrubber, or more accurately the relationship of the volume of gas swept to the total volume of gas, is then expressed by $1.5\ RW/dQ$ where "Q" is the quantity of gas. This expression obviously is of importance in determining the efficiency of collection.

It is apparent that if it were possible to sweep a given quantity of dirty or original gas completely in an instant, all the dust would be removed and the collecting efficiency would be 100%. This obviously is a physical impossibility since a solid water curtain would be required. What actually

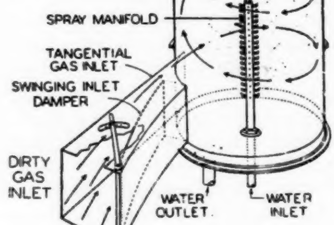



Fig. 1.
Cyclonic Spray Scrubber

happens is that only the first drops to contact the dirty air are fully effective since all other drops sweep air that has been partially cleaned. Even if these droplets remove all the particulate matter from the air they sweep, the absolute amount removed per unit of spray water decreases for each succeeding spray head or curtain. The amount of pollutant remaining in the air stream decreases exponentially and is expressed by the relation $E = 1 - e^{-n}$ where "E" is the absolute efficiency, "e" is the natural log base, and "n" is the ratio of the gas swept by the water droplets to the total gas quantity. Since the ratio of the gas swept to the total gas quantity was shown earlier to be 1.5 RW/dQ, this factor may be substituted for "n" and the expression becomes $E = 1 - e^{-1.5RW/dQ}$ where "W" and "Q" are given in cfm, and "R" and "d" are comparable units, say feet or inches. When the gas being cleaned is washed or swept once, that is, when $1.5RW/dQ = 1$, the collecting efficiency is 63.2%, when it is 2, the efficiency is 86.4% and when it is 3, the efficiency is 95.0%. Converting the foregoing relationship to more convenient terms it becomes $E = 1 - 10^{\left(-26544\frac{RW}{dQ}\right)}$ where "R" is in feet, "W" in gpm, "d" in microns, "Q" in cfm, and 10 is the common logarithm base. Under the conditions described in the foregoing analysis, the theoretical efficiency of a four-foot diameter scrubber in which droplets of 100 micron average size are produced is 71% if the rate of water spray is one gallon per thousand cubic feet of air, 91% if two gallons, and 97% if three gallons per thousand cu. ft.

Anyone who has had experience with conventional spray scrubbers knows that these theoretical efficiencies are not attained in practice. There are several reasons for this. Probably the most important ones are that the spray does not produce droplets of the small diameter that is most effective and that the particles are not caught or swept from the air stream even if hit by a droplet. There is evidence to indicate that if the droplet diameter is more than about 200 times the diameter of the particle to be removed, it will not sweep the particle out because the stream-lining around the drop as it approaches the particle causes the latter to pass around the water droplet.[3] Hence for particles one micron in diameter the water droplets should be less than 200 microns in size and for smaller particles such as some fumes even smaller droplets are needed. To produce such small droplets is difficult both because of the pressure required and the plugging of very fine nozzles. Not many types of sprays produce droplets of the fineness needed to be most effective. Relatively few droplets smaller than 1000 microns in diameter are produced by conventional sprays. Hence, such sprays are very ineffective in particulate matter removal both because the fine particles are not hit and because the amount of gas swept per unit of spray water decreases rapidly as the droplet size increases. For example, to accomplish one complete sweep of the gas requires 8.2 gal. of water per 1000 cu. ft. of gas if the water droplets produced are 1000 micron in size, 2.5 gal. if 300 microns, and 0.8 gal. if 100 microns in diameter. The importance of droplet size is even more evident from Table I which gives the theoretical cleaning efficiency of a 4-ft. diameter scrubber at different water rates and for three different droplet sizes.

TABLE I.
INFLUENCE OF DROPLET SIZE ON COLLECTING EFFICIENCY OF A FOUR-FOOT DIAMETER SPRAY SCRUBBER

| Water rate (gals./ 1000 cu. ft.) | Percentage Collecting Efficiency for water droplets | | |
|---|---|---|---|
| | 1000 microns in diameter | 300 microns in diameter | 100 microns in diameter |
| 1 | 11.5 | 33.5 | 70.6 |
| 2 | 21.7 | 55.7 | 91.3 |
| 3 | 30.7 | 70.5 | 97.4 |
| 4 | 38.7 | 80.4 | 99.2 |
| 5 | 45.7 | 87.0 | 99.8 |
| 6 | 52.0 | 91.3 | 99.9 |
| 7 | 57.5 | 94.2 | 100.0 |
| 8 | 62.4 | 96.2 | |
| 9 | 66.7 | 97.4 | |
| 10 | 70.5 | 98.3 | |
| 11 | 73.9 | 98.9 | |
| 12 | 76.9 | 99.2 | |
| 13 | 79.6 | 99.5 | |
| 14 | 81.9 | 99.7 | |
| 15 | 84.0 | 99.8 | |
| 16 | 85.9 | 99.9 | |
| 17 | 87.5 | 99.9 | |
| 18 | 88.9 | 99.9 | |
| 19 | 90.2 | 100.0 | |
| 20 | 91.3 | | |

In addition to droplet size, there are other factors that affect the operation of spray scrubbers. The kinetic energy of small droplets is expended rapidly making it impossible to project them very far through air streams, and some auxiliary force, such as centrifugal motion, must be used to cause

the droplets to move the distance required. Evaporation of fine droplets in hot gas and incomplete removal of them from the air stream also affect the collecting efficiency adversely.

Let us turn now to types or models of collectors in common use. Omission of any specific type or make of collector from this discussion must not be construed to imply that such device is inefficient or unsatisfactory for any reason whatsoever. It is impossible to mention all wet collectors,—some must be omitted.

Wet collectors that make use of the principle of air washing, alone or primarily, include the following but are not limited to them. (1) Spray chambers or towers. (2) Cyclonic spray scrubbers. (3) Venturi scrubbers. (4) Disintegrators. (5) Fog nozzles.

Conventional spray chambers or towers are numerous. Witheridge described several recently that are used on the stacks from foundry cupolas.[4] Homemade models are common. Water rates frequently used in commercial models range from 5 to 20 gal. per thousand cu. ft. of dirty air. Collecting efficiencies apparently are influenced a great deal by the particle size of the pollutant. Thus for dusts, efficiencies by weight of 90 to 99% are not uncommon. For freshly generated fumes of small particle size much lower collecting efficiencies would be expected. It is difficult to say what these values may be since they apparently vary widely because of droplet size, degree of mixing of the air and water, and the rate of water consumption. Some reports give results as high as 96 to 98% and there is other information to indicate that it may be as low as 50 to 60% under certain conditions. A range of 50 to 90% probably covers most spray scrubber installations for fumes. Collectors of this kind alone are often incapable of resolving an air pollution problem, but they are extremely useful as primary collectors so as to reduce the dust loading to a point where the gas can be cleaned effectively by means of secondary cleaners.

The only important difference between the cyclonic spray scrubber (see Fig. 1) and the simple spray scrubber is that centrifugal motion is employed to carry the water droplets across the air stream from the axial spray manifold to the shell of the scrubber. Whereas the centrifugal motion will tend to carry some of the large particles to the walls of the scrubber, this factor plays no important part in the operation of it. The rotation of the air in the scrubber is essential to cause the fine water droplets to move across the air stream before the longitudinal motion induced can carry them through the collector. As shown in the figure, there is need for an unsprayed section in the down stream end of the scrubber (with respect to air flow) so that the water droplets containing particulate matter that has been swept from the air have time to move to the walls of the collector before the gas stream emerges. If the sprays of the scrubber produce large water droplets, they can be projected to the walls of the collector by the kinetic energy imparted by the water pressure, but as shown previously large water droplets are not as effective in removing the contaminant from the air stream. The pressure loss across such collectors is very small being essentially the shock loss attributable to expansion and contraction plus that required to set the water droplets in motion.

Relatively recently so-called Venturi scrubbers have been placed on the market (see Fig. 2).[5,6] These scrubbers were designed to obtain good diffusion for removing gases and extremely fine particles but have

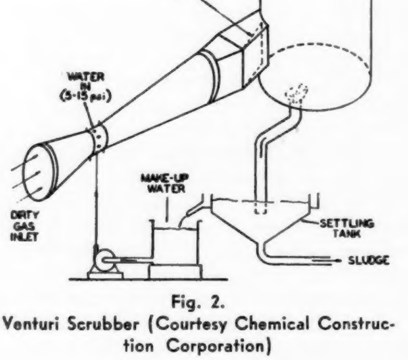



Fig. 2.
Venturi Scrubber (Courtesy Chemical Construction Corporation)

been found to be unusually effective against the usual-size particulate matter. The velocity of the air to be cleaned is accelerated to about 12,000 to 30,000 fpm in the Venturi throat where it strikes the spray water which is introduced at right angles to the air stream either through the collar as shown in the figure or by means of internal piping. Water pressure is usually 5 to 15 *psi* but good disintegration of the water is produced by the air velocity. The high velocity serves also to accomplish good air and water mixing increasing the probability of collision between the droplets and particles. The water consumption ranges from 2 to 9 gal. per thousand cu. ft. of gas, 3 to 6 being the common rates. The pressure loss is a function of the throat velocity and the quantity of water used, and is usually about 15 in. of water although values as high as 24 in. are sometimes experienced. As indicated in the figure, an auxiliary collector or separator is needed to remove the water droplets from the gas stream. The collecting efficiency of this unit is higher than that of simple spray towers and probably higher than that of any other type of wet collector. For dusts and particulate matter of the usual size encountered, good removal is obtained at lower pressure losses, about 12 in. of water.

Disintegrators have been used for many years in the steel industry for gas cleaning purposes. They have not been used widely elsewhere to my knowledge and deserve little discussion before this group. These devices are squirrel-cage fan type devices in which the water is churned violently in one direction while the dust-laden air passes through the unit in the opposite direction. Disintegrators are true air washers since the cleaning is accomplished primarily by the churning or scrubbing effect of the water in the air stream.

Fog filters are a relatively recent addition to the field of wet collectors.[7] These filters are essentially simple spray washers in which special nozzles and very high water pressures are used to get good water disintegration. The recommended spray pressure is about 400 *psi*. The nozzles may be located directly in existing stacks, in dry cyclones, or in spray type heat exchangers. Sometimes they are housed in a tower or chamber which forms part of the dust collector installation. The water consumption is about 7½ to 10 gal. per thousand cu. ft. of dirty air. Auxiliary collectors or sprayers may be needed to remove the fine water droplets from the air stream. Pressure loss, as with simple spray washers, is low. The collecting efficiency apparently is influenced greatly by the type and fineness of the matter to be removed. Values of 70 to 99% have been reported.

Wet collectors which employ combinations of the principles of washing and particle inertia or centrifugal force include the following: (1) Wet filters. (2) Deflector washers. (3) Centrifugal washers. (4) Miscellaneous.

Most types of commercial washers make use of combinations of washing, sudden directional changes, and continuous directional change to capture the particulate matter. The air direction may be changed suddenly a number of times in succession to cause the particles near the outer edge of the stream to drift out and be captured by the wetted surface guiding the stream. The water may be tossed about or sprayed so that it passes through the air stream time and again.

Wet filters are washing towers or chambers in which the water is supplied to closely woven screens or filtering materials such as copper filings, hogs hair, or vegetable or synthetic fibers. As the air passes through the filters the dust particles are brought in close contact with the large wetted surface area exposed by the filter or successive filters. Some of the particles then drift to the wetted surfaces of the filter elements and are captured. Collectors of this type play a much more important role in the removal of gaseous contaminants than of particulate matter and probably will be described in more detail by another of the speakers.

Deflector washers are many and varied. They operate by (1) causing the dirty air stream to change direction suddenly one or more times, thereby throwing some of the particulate matter out of the air stream against the collecting liquid or wetted surface, and (2) churning or spraying the liquid in such fashion that it is thrown through the gas stream one or more times. The directional changes may be produced by baffles, plates, or discs across parts of the air stream at appropriate points. The water dispersion may be accomplished by spraying directly into the air stream, by

spraying onto surfaces of contact, or by causing the air to churn the water.

Examples of wet collectors of this kind include the Type N Rotoclone, the Uni-Wash Dust Collector, the Multi Wash Dust Collector, the Hydro Whirl Dust Collector, and the Centrimerge Dust and Fume Eliminator. Some of these are illustrated in Figs. 3 through 6. There are others, of course,—the foregoing are by way of example to illustrate the features of this type of collector.

The nature of operation is evident from a study of the figures. The pressure loss across this group of collectors is about 2.5 to 4 inches of water at rated capacity. Collecting efficiencies are influenced a great deal by particle size, and probably range from 60 to 99%. Water consumption varies from almost nil to about 6 gal. per thousand cu. ft.

Centrifugal washers are comparable to deflector washers except that a continuous direction change replaces the sudden direction change of short duration. Examples of this type are the Air Tumbler and the Type W Rotoclone (see Figs. 7 and 8). In fact, any centrifugal fan with a water spray located at the center of the inlet and spraying on the impeller is a centrifugal washer. Obviously the rate of water sprayed must be sufficient to exceed the evaporation rate and to carry the collected dust to a hopper or other collecting basin. If the spray water is not adequate, some of the wetted material may adhere to the impeller and unbalance it, thereby causing fan failure. Witheridge shows a different design of centrifugal collector in his paper on cupola stack collectors.[4]

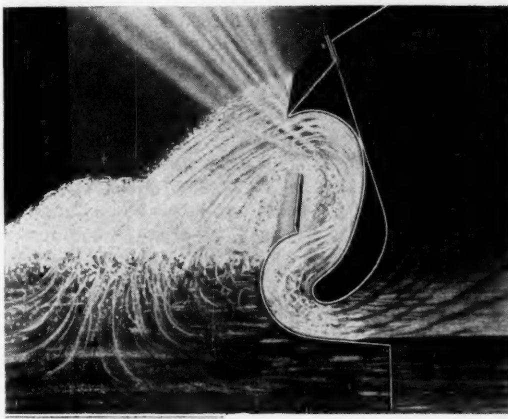
There is little need to discuss this type of wet collector here because most of the collecting influence is centrifugal force, which has been covered by a previous speaker. While the water may have a washing effect in some of the centrifugal washers, more commonly it merely serves to retain the particulate matter thrown to the periphery by centrifugal motion and to convey it to the settling basin or point of disposal. The collecting efficiencies and the pressure losses are therefore about the same as the comparable dry centrifugal precipitators. Water consumption is unusually low and varies from almost nil to about 4 gal. per thousand cu. ft.

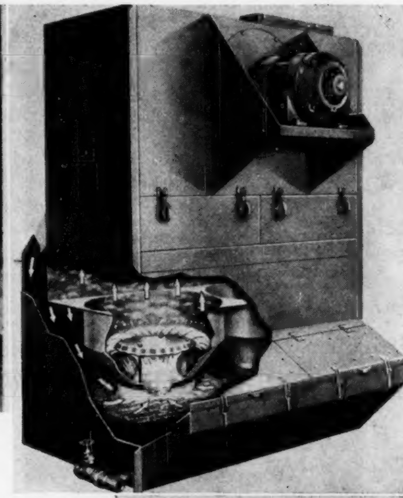
Some wet collectors employ a combination of all three capturing principles, centrifugal motion, sudden abrupt change, and washing. This type of collector is illustrated in Fig. 9. In this particular model a detergent is added to the water for the purpose of increasing the wettability of the dust particles, and to cause a foam bed to be formed above the liquid so that the air stream must pass through it as it rises toward the collector outlet. Water consumption rate is very low since the collecting liquid is reused.

IT MIGHT be well to refer briefly to the use of detergents or wetting agents in wet collectors and especially in spray curtains. Whether the addition of detergents to the water used for particulate matter collection improves the collecting efficiency significantly is a controversial subject. I do not intend to argue the matter. It seems logical that wetting agents should improve the effectiveness of dust removal in some collectors and against certain contaminants. It has been my experience and that of some few others that the efficiency is not improved measurably in certain instances by the addition of wetting agents to the water in the collector. Certainly the use of wetting agents in scrubbers or in sprays is not the panacea for all air pollution ills. Some detergent suppliers are advocating their products rather strongly for use in spray curtains in stacks and even as final cleaners following other ineffective collectors. Even if the addition of the wetting agent to the water improves the probability of a "catch" during collision of the droplet with the particle, the droplets cannot possibly remove the particles they do not hit, and, as shown previously, producing a high percentage of hits by means of water curtains is difficult.

It is difficult to list the advantages and disadvantages of wet collectors as a group because the very factor that gives the wet collector its advantage in one instance may act to its disadvantage in another. However, certain general statements may be made to suggest the basis upon which the advantages and disadvantages may be compared with those of other collectors in selecting one for a specific operation.

In wet collectors the material removed from the air is held in the water preventing it from creating a secondary dust problem in subsequent handling, preventing it from





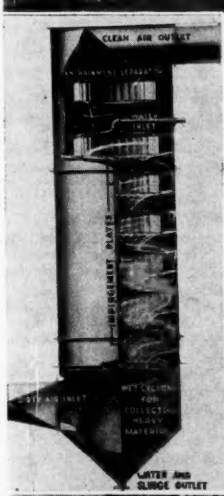
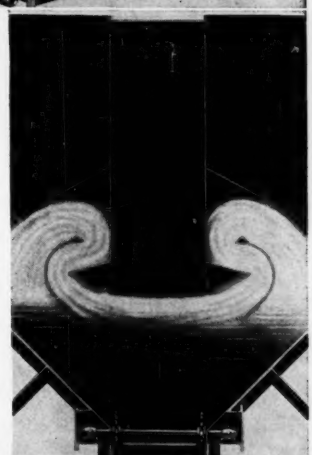
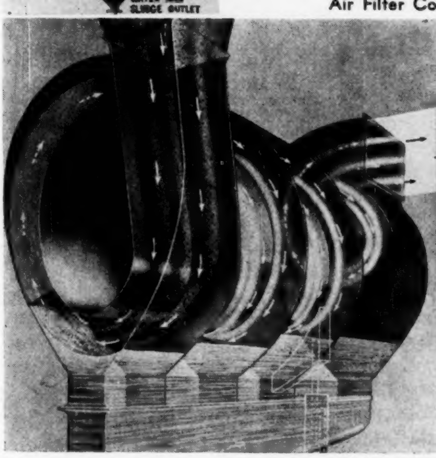



Fig. 3. (Upper Left).
Type N. Rotoclone (Courtesy American Air Filter Company)
Fig. 4 (Upper Right).
Uni-Wash Dust Collector (Courtesy Newcomb-Detroit Company)
Fig. 5 (Left).
Multi-wash Collector (Courtesy Claude B. Schneible Company)
Fig. 6 (Right).
Centrimerge Dust and Fume Eliminator (Courtesy Schmeig Industries, Inc.)
Fig. 7 (Lower Left).
Air Tumbler (Courtesy Dust Suppression Engineering Company)
Fig. 8 (Lower Right).
Type W Rotoclone (Courtesy American Air Filter Company)





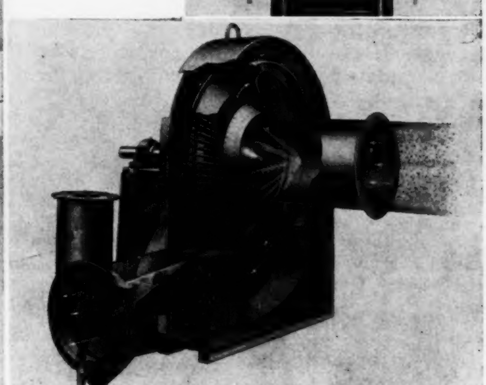



Fig. 9.
Hydro-Foam Dust Collector (Courtesy R. C. Mahon Company)

presenting a fire or explosion hazard in subsequent handling, and making disposition easy if it can be discharged to the sewer or nearby stream without creating a nuisance. However, if the material is to be reused or sold in the dry state, or if it goes into solution or does not settle readily, and must be removed before the water can be discharged, the wet procedure is disadvantageous. If the air from the collector is to be recirculated to the room or building to conserve heat, the high humidity may create a moisture condensation problem. If the gas or air to be cleaned is hot, the wet collector will serve as a cooler which is usually desirable except in those instances where further use can be made of the heat contained in the hot gases. The pressure loss across wet collectors is constant, a condition not prevailing in all types of collectors. Certain wet collectors require large amounts of water creating a problem of water supply or water cleaning and reuse. Some wet collectors require high water pressures so that auxiliary pumping equipment is needed. If fine sprays are called for to get effective collection, the nozzles plug and cause operational difficulties. The successful operation of most wet collectors is not affected adversely by extremely heavy dust loadings; some types of collectors are so affected. The collecting efficiency, as with most types of collectors, varies a great deal from job to job depending upon the size, specific gravity, composition, shape and wettability of the particulate matter to be removed.

## References

1. PENDRAY, G. E.: Paper entitled "Public Relations Aspects of Industrial Wastes" presented at Industrial Waste Conference, Industrial Hygiene Foundation of America, Pittsburgh, November 18, 1949.

2. BRANDT, A. D.: Paper entitled "Problems in Air Pollution" presented before Philadelphia Section Association of Iron and Steel Engineers, Philadelphia, December 3, 1949.

3. KLEINSCHMIDT, R. V.: "Factors in Spray Scrubber Design." *Chemical & Metallurgical Engineering*, Vol. 46, August, 1939.

4. WITHERIDGE, W. N.: "Foundry Cupola Dust Collection." *Heating & Ventilating*, 46:12, December, 1949.

5. JOHNSTONE, H. F., and ROBERTS, M. H.: "Deposition of Aerosol Particles from Moving Gas Streams." *Industrial & Engineering Chemistry*, 41:11, December, 1949.

6. JONES, W. P.: "Development of the Venturi Scrubber." Ibid.

7. HUDSON, D. G.: Paper entitled "The Principle of the Fog Filter," given at the Annual Meeting of the AMERICAN INDUSTRIAL HYGIENE ASSOCIATION, Detroit, April 7, 1949.

# Electrostatic Precipitation and Sonic Flocculation

HILLARY W. ST. CLAIR, Ph.D.,
Head, Metals Recovery and Refining Section,
Eastern Experiment Station, U. S. Bureau of Mines,
College Park, Maryland

THE removal of suspended particles from gases was suggested by Hohlfeld as early as 1824 but the first attempt to precipitate industrial smoke electrically was made at the Dee Bank Lead Works in England by Sir Oliver Lodge in cooperation with Alfred O. Walker. The only description of this installation now available seems to be the description in a patent issued to Walker in 1884. The apparatus is described "as consisting of a system of metallic points situated in the flue from the lead furnaces and excited from two Wimhurst influence machines with glass plates 5 feet in diameter, each machine being driven by a 1 hp. steam engine." Evidently the apparatus did not perform as expected as there is no further record of it in the technical literature.

In about 1905 F. G. Cottrell, working on the problem of removing acid mists from gases treated by the contact sulfuric acid process, repeated the experiments of Lodge. He succeeded in solving the practical problems of devising suitable high potential generators for applying the effect first to acid mists and then to smokes produced in nonferrous smelters, dusts from cement plants and other industrial smokes. Dr. Cottrell's work was the beginning of electrical precipitation as we know it today.

Electrical precipitators for industrial smokes may be divided into three different classes according to the major purpose:

1. Recovery of valuable material in the smoke—for example, recovery of lead, silver, cadmium and other valuable metals from the fumes of blast furnaces.

2. Removal of poisonous materials or nuisance materials from gases exhausted to the atmosphere—for example, removal of arsenic from smelter fumes or fly ash from flue gases of power plants.

3. Cleaning gases for industrial use—for example, cleaning of gases for manufacture of sulfuric acid or cleaning of blast furnace gases to be used as fuel.

For many years electrical precipitation was applied only to industrial smokes but more recently it has found wide application for cleaning air in air conditioning plants. It is finding more and more application particularly in the ventilation of pharmaceutical plants, ball bearing manufacturing plants, museums, hospitals, offices and also homes. Recently there have been many installations for removing oil mist from the air near high speed grinders and other machine tools. In many such applications the value of the oil recovered pays all or a large part of the cost of operation of the precipitation unit.

Electrical precipitation may be considered as a sequence of the following four steps:

1. Charging of the suspended particles by means of gaseous ions or electrons;
2. Transporting of the charged particle to the collecting electrode by interaction of the charge and electrostatic field;
3. Discharging the particles;
4. Removal of the precipitated particles from the collecting electrode.

The ions and electrons for the charging of the particles are produced by the corona discharge from the charging electrode. When a high voltage is applied across two electrodes in air, at a certain potential, depending on the shape and spacing of the electrodes, a current will begin to flow because of ionization of the air. If the potential is increased further to the breakdown

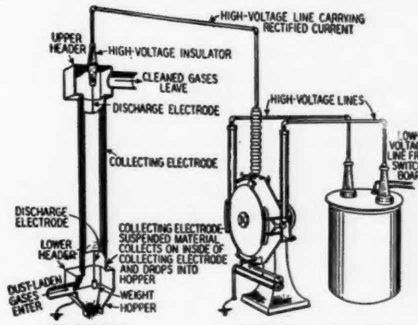



Fig. 1.
Apparatus employed in electrostatic precipitation

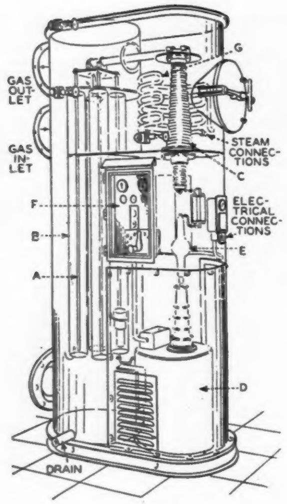



Fig. 2.
Complete unit for electrostatic precipitation of dust and smoke

potential the air is completely ionized between the electrodes and an electric arc is formed between the electrodes. The relatively slow discharge that occurs between the sparking potential and the breakdown potential is known as a corona discharge.

The discharge or collecting electrode is usually charged with a positive potential. Negatively charged particles migrate to the collecting electrode and are thereby separated from the gas. Cottrell also experimented with alternating fields and found that electrostatic agglomeration was produced similar to that observed in sonic agglomeration. Some applications have been found for electrically induced agglomeration; for example, in the precipitation of finely divided magnesium powder produced in electrothermic reduction of magnesia.

The transfer of the charged particle to the collecting electrode is usually given undue importance in most discussions on the theory of electrical precipitation. Actually the charging and discharging of the particles are of greater importance in determining the applicability and limitations of the process.

The maximum rate of precipitation is often actually determined by the rate of discharge at the collecting electrode. When the particles are poor conductors of electricity an insulating layer of particles is built up on the electrode; subsequent layers of particles cannot be discharged and so a counter charge is built up that nullifies the electric field between the electrodes and stops further precipitation. This difficulty is usually alleviated by increasing the humidity of the gas or in some other way increasing the electrical conductivity of the layer of the precipitated particles.

The removal of collected material from the electrode is a mechanical problem but one that frequently calls for a good deal of ingenuity.

Precipitators for industrial gases usually operate at a potential of 40,000 to 60,000 volts. The potential is stepped up from line voltage with a high-voltage transformer and rectified by a rotary commutator driven by a synchronous motor. More recently thermionic rectifiers have been used in the place of mechanical rectifiers, particularly in smaller installations. Rectifier power packs are available having current capacities of 300 to 400 milliamperes. The current requirements usually range from 50 milliamperes to several amperes. When the current requirements exceed the capacity of a single rectifier several rectifiers may be operated in parallel.

Precipitators for air conditioning usually require only 10,000 to 15,000 volts. A high voltage is applied to the charging electrodes and about half that voltage is applied to the collecting plates. Electronic rectifiers are used for these units since most installations require capacities of less than 100 milliamperes or not more than several hundred milliamperes in the largest installations.

Precipitators for industrial smoke are of two general types: plate treaters and pipe treaters. Pipe treaters are used for the smaller installations. The gases are passed through a bank of vertical pipes 4 to 12 inches in diameter. In this type of precipitator the charging and collecting is done by the same pair of electrodes. The corona discharge is formed around an insulated wire hanging vertically along the axis of the pipe. The walls of the pipe act as the collecting electrode. At periodic intervals the power is turned off and the pipes are rapped mechanically to discharge the precipitated deposit to hoppers below.

The plate or rod curtain precipitators are similar in operation to the pipe treaters except that the smoke is passed between paral-

lel plates or curtains made of rods. The charging electrodes consist of rows of insulated wires midway between the plates.

Precipitators used for air cleaning employ separate systems of electrodes for charging and collecting the particles so arranged as to minimize the amount of ozone formed. An electric charge is induced on air-borne particles as the air passes between thin tungsten wires at high potential located midway between parallel metal tubes at ground potential. The charged particles then pass between alternate rows of positive and negative charged plates that act as collector electrodes. Upon contact with the plates the particles lose their charge but continue to adhere to the plate partly by agglomeration and partly by an adhesive coating applied to the plate. The collector plates are cleaned at intervals by de-energizing them and flushing with hot water. After each washing the plates are sprayed with a new coat of adhesive and are ready for operation again.

## Sonic Flocculation

THE agglomeration of suspended particles in smoke and fume was observed independently by Brandt, Freund and Hiedemann in Germany, by Andrade and his coworkers in England and by St. Clair in the Bureau of Mines laboratory at Minneapolis, Minnesota. Following the first observations on the phenomenon, a fundamental study was made by the Bureau of Mines of the behavior of suspended particles under the influence of intense sound waves and of various problems relating to generation of sound fields of great intensity. The objectives of this investigation were to provide the scientific information on which to base the engineering and design of a practicable unit for utilizing the effect for treating industrial smokes.

The generation of sound of the intensity required for sonic flocculation introduces entirely new problems not heretofore encountered in acoustical engineering. Vibrating diaphragms and plates, ordinary whistles and sirens, and other such sources of sound are entirely inadequate for reaching the frequencies and intensities required for sonic agglomeration.

The first type of generator to be used was a magnetostriction vibrator or a nickel tube excited into vibration by placing it in a coil through which is passed alternating current of the proper frequency. Nickel, being a magnetostrictive metal, alternately increases and decreases in length in response to the changing magnetic field. If the frequency of the applied current is adjusted to vibrate the nickel tube at its resonant frequency, the end of the tube, to which is welded a radiating piston, becomes a powerful source of high frequency sound.

Another type of generator which has been used is the quartz steel sandwich devised by Langevin during World War I for underwater signaling. A mosaic of carefully ground quartz crystals is placed between two identical thick steel plates. The quartz and steel surfaces are carefully lapped to give very good contact between the two surfaces. When an alternating potential is applied to the two steel plates, the quartz crystals undergo electrostrictive deformation and the unit is set into vibration. The quartz steel sandwich has a resonant frequency corresponding to that of a steel rod having a length slightly greater than twice the thickness of each steel plate. Generators of this type are known as piezo electric generators; they are the electrostatic analogue of magnetostriction generators.

The generator that was employed for the study made by the Bureau of Mines, was a cylindrical bar of aluminum alloy excited into vibration electromagnetically in a manner similar to that employed in driving a dynamic loudspeaker. This type of generator was particularly advantageous for experimental work because of its high efficiency and because it permitted a great number of measurements on the characteristics of the generator and the sound field to be made through the reaction in the electrical circuit.

All of the foregoing types of sound generators may be considered as a modification of a vibrating piston. Another type of generator that offers many advantages in practical application is that in which the sound is generated by rapid pulsations of compressed air or gas. One generator of this type used in the early experiments is the Hartmann generator, the essential feature of which is a supersonic air jet directed into the open end of a small closed end cylinder. The gas in the cylinder is thereby excited into intense vibration and behaves as a very small organ pipe. Generators of this type behave approximately as point

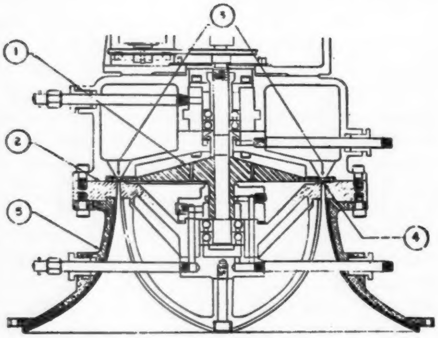


Fig. 3.
Siren type acoustic generator. (From Industrial and Engineering Chemistry, 41:11, November, 1949, Harold W. Danser and Ernest P. Neumann, "Industrial Sonic Agglomeration and Collection Systems")

source of sound rather than a vibrating piston.

The foregoing generators are all suitable for sonic agglomeration on a small scale and in principle could be applied on an industrial scale. However, the maximum power that has been radiated by such generators is of the order of a few kilowatts. For industrial application a practicable generator should have an output of 50 kilowatts or more per unit.

Recently siren-type generators have been developed that generate high frequency sound on the scale of 10 to 50 kilowatts per unit. These generators are similar in principle to the ordinary siren but are epecially designed for frequencies of the order of 10 kilocycles or more. The essential feature of such a generator is a rotor with a large number of equally spaced ports around the periphery which are matched to similar ports on a stator. The rotor is rotated at high speed either by an air turbine or by a high-speed electric motor. As the rotor turns, the ports are alternately opened each time the ports match and closed during the intervening period. Air or gas under pressure in the chamber behind the rotor flows out in periodic pulses through the ports. The frequency of the sound is determined by the number of ports in the rotor and stator and the speed of the rotor. The intensity is determined by the pressure of the gas in the pressure chamber. One type of generator now being manufactured has a nominal capacity of 50 kilowatts. Generators of greater capacity are being developed.

All dispersions of finely divided liquids or gases, such as smoke or fog, undergo spontaneous agglomeration because of random collisions of the particles. But the rate of spontaneous flocculation is imperceptible for most industrial smokes. Under the influence of intense high frequency sonic vibrations, new forces are brought into action that cause rapid agglomeration of smokes that would otherwise remain stable. These forces are manifold and not yet sufficiently well understood to permit other than a qualitative explanation. It was concluded from early experiments that flocculation was due to increased rate of collison resulting from vibratory motion of the particles but further study revealed that there were also positive acoustic and hydrodynamic forces acting to bring the particles in contact with each other. The primary cause of sonic agglomeration is found to be acoustic radiation pressure. Agglomeration of smoke particles is caused by the same forces that produce the striations in lycopodium powder obesrved in the Kundt dust tube experiment, usually performed as one of the laboratory experiments in college physics.

The essential elements of a sonic flocculator are a sound generator coupled to a resonant enclosure. A non-uniform sound

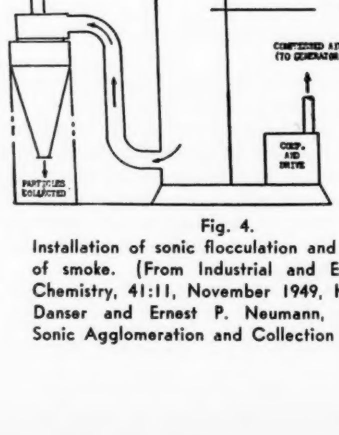


Fig. 4.
Installation of sonic flocculation and collection of smoke. (From Industrial and Engineering Chemistry, 41:11, November 1949, Harold W. Danser and Ernest P. Neumann, "Industrial Sonic Agglomeration and Collection Systems")

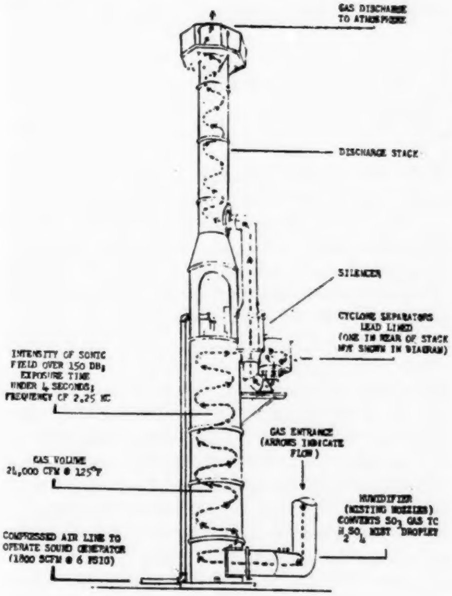



Fig. 5.
Sonic collector for sulfuric acid mist. (From Industrial and Engineering Chemistry, 41:11, November, 1949, Harold W. Danser and Ernest P. Neumann, "Industrial Sonic Agglomeration and Collection Systems")

field or system of standing waves is set up in the enclosure. Although agglomeration is produced by a uniform progressive wave, a non-uniform field is very much more effective.

When a flocculation experiment is carried out at relatively low intensity in a glass enclosure, the successive stages of flocculation may be observed. Just before flocculation becomes visible the smoke takes on a banded appearance owing to migration of the particles to the antimodal regions or positions of maximum amplitude. Shortly afterward the smoke begins to take on a granular appearance as the flocs become large enough to be seen. The flocs are wafer-shaped and at low intensities orient themselves with their planes normal to the direction of vibration.

At high intensities flocculation takes place in a few seconds. Large flocs are no longer formed because of the instability of the sound field. Rapid agglomeration requires intensities of the order of 1 watt per square cm.

It is only within the last few years that sonic flocculation has begun to be applied industrially. The phenomenon was observed about 14 years ago but much had to be learned concerning the generation of high frequency sound on the scale of many kilowatts per unit and other peculiar characteristics of sound of great intensity before it became feasible to attempt industrial application. There is still much to be learned, particularly regarding the properties of sound fields of great intensity, but sonic flocculators have now established themselves as practicable tools for combatting certain phases of the smoke problem. It is still too early to give an appraisal of their relative position among the other tools used for precipitation of dust and smoke.

# Gas and Vapor Absorption and Adsorption

J. LOUIS YORK, Ph.D.,
Department of Chemical and Metallurgical Engineering,
University of Michigan,
Ann Arbor

THE previous papers in this group have been concerned primarily with removal of particulate matter from a gaseous phase by a physical means. Another important class of contaminants is the group of vapors which are undesirable because of odor or noxious effect on plant and animal life. These are not affected by most of the particle-removal devices. An earlier paper in this symposium discussed chemical means of transforming these pollutants or removing them, along with particulate matter in many cases. The physical means of separating undesired vapors from the carrier gas are divisible into two principal categories, absorption and adsorption.

Technically, absorption occurs when the material being absorbed (the undesirable vapor in this case) moves completely into the absorbing substance, with the molecules of the vapor entering into and disrupting to some extent the intermolecular forces of the absorbing substance. Another way of describing absorption is that the vapor is dissolved in the absorbing substance, forming a homogeneous solution. The absorbing substance is usually a liquid but might be a solid in rare cases.

Adsorption occurs when the vapor is attracted strongly to the surface of the adsorbing substance, but the molecules of the vapor do not enter into the intermolecular forces of the adsorbing substance. The forces of attraction holding the molecules to the surface of the adsorbing substance are quite high, in many cases approaching the magnitude of the intermolecular forces. Another way of describing adsorption is that the vapor is highly concentrated on the surface of the adsorbing substance without penetrating it. The adsorbing substance is usually a solid, but occasionally may be a liquid. Because most commercial adsorbents are extremely porous solids, with minute pores causing increases in the actual surface areas ranging up to several hundred thousand times the apparent surface area of the particle, the adsorbed vapor appears literally to have entered into the particle, but actually it enters the pores and is adsorbed on their surface.

The theoretical aspects of both absorption and adsorption are based on equilibrium relations, and much of the discussion of one is also a discussion of the other. Absorption will be taken up first.

## Absorption

EQUILIBRIUM between two phases, with a common component appearing in each phase, exists when an active transfer of the common component occurs in opposite directions at equal rates. For absorption the vapor is being absorbed from the gas exactly as fast as it is being released to the gas from the absorbent. Any alteration in the sensitive balance of the equilibrium will cause an immediate shift in the concentrations. For example, an increase in concentration of vapor in the gas phase will be followed quickly by an increase in the absorption of the vapor into the absorbent. The reverse flow from the liquid to the gas is governed by the concentration in the liquid and will not respond so quickly. The result is a net transfer of vapor to the liquid until the increasing concentration in the liquid and the decreasing concentration in the gas re-establish a new equilibrium at a new level of concentrations.

The simplest version of equilibrium in a mathematical equation is

$$y = kx$$

where y represents the average concentration of the vapor in the gas phase in equilibrium with an absorbent, x represents the average concentration of the vapor in that absorbent, and k represents an equilibrium coefficient. The coefficient is a function of the nature of the vapor, the absorbent, and the carrier gas, as well as a function of concentration of the vapor, temperature, and pressure. The values of the coefficient rarely follow simple laws, and less rarely do they remain constant for any appreciable range of concentrations, therefore they must be determined experimentally for all systems.

Continuous flow of the gas phase past the

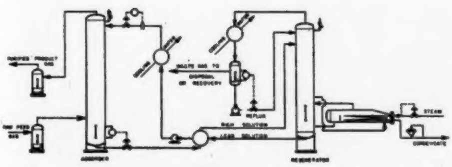


Fig. 1.
A typical absorption system with regeneration and re-use of absorbent

liquid phase does not affect the tendency toward equilibrium, but the brief time of contact allowed by the flow may not be enough to permit attainment of it. In actual practice, absorption usually is conducted with both phases flowing in opposite directions. A tower is commonly used if the contact between phases is to be prolonged more than a few seconds, with the liquid absorbent falling down through the tower by gravity and the gas being forced up through the tower by a blower. Fig. 1 shows such a tower as part of a system which includes a regenerator. The liquid dissolves vapor continuously and increases in concentration as it proceeds down the tower. The gas is in contact with the highest concentrations of liquid first, then meets decreasing concentrations of liquid farther up the tower as it also decreases in concentration. The difference between the actual vapor concentration in the gas and the concentration which would be in equilibrium with the liquid may thus be maintained reasonably constant along the entire active height of the tower. The local rate of absorption is dependent on this difference in concentration and the actual level of concentration at each point in the tower.

Removal of a specified amount of undesirable vapor from a specific quantity of gas requires the use of an absorbent which can be introduced into the top of the tower at a concentration well below that which would be in equilibrium with the gas leaving, thus establishing a concentration gradient to permit absorption. The liquid must be supplied in sufficient quantity that it does not reach a concentration in equilibrium with the entering gas, else it will be unable to dissolve the specified amount of vapor. The minimum amount of liquid to satisfy the specification is that amount which will just barely reach this equilibrium concentration as it leaves the bottom of the tower past the entering gas. But this minimum amount of liquid will dissolve the specified vapor only if the tower height is infinite. Increasing the liquid rate above the minimum will establish a finite concentration gradient at all points in the tower, and will reduce the necessary height to a workable finite value. As the liquid rate is increased the tower height decreases, quite rapidly as the rate approaches twice the minimum, but slowly beyond that. The increased liquid rate, however, means a more dilute exit liquid and therefore more expensive regeneration later. The liquid rate thus helps to fix a major dimension of the tower. Usually the optimum liquid rate is 1.5 to 2.5 times the minimum value.

The gas velocity is the second specification affecting the dimensions of the tower. The velocity must not be so low that an excessively large diameter tower is needed to treat the gas, nor can it be so high that the time of contact with the liquid is too brief for the specified absorption unless the tower is excessively high. Occasionally the absorption is so rapid that the height limitation is not serious, and the upper limit of velocity then becomes that which blows liquid out of the tower. General figures cannot be given for this operating and design variable, for it is greatly dependent on the coefficient of absorption and nature of the vapor and absorbent, as well as the inner construction of the tower.

### Absorber Construction

THE rate of absorption is directly proportional to the area of contact between the gas and liquid, therefore important reductions in the size of the tower can be effected if this area is increased substantially. The many different designs of packing for towers reflect the intense effort expended to obtain an efficient and economical increase in the area of contact.

An obvious and simple technique for increasing the area is spraying the liquid into the gas and allowing it to settle down to the bottom of the tower. The previous paper described equipment of this type as it is designed to remove particulate matter, usually with water as the liquid. If the undesirable vapors are soluble in water such equipment is somewhat more effective as an absorber than as a particle washer. Most of these devices are not selected, how-

ever, when absorption of undesirable vapors is the principal goal, for most of them require such large quantities of liquid that the concentrations are too low for economical removal of the vapor from solution (unless the liquid is recycled several times), even though they may be too high to allow disposal by dumping. Most washers allow far too brief a time of contact for most absorption operations, with appreciable energy requirement as an additional deterrent.

A more complex method of creating area of contact, but without serious energy demands, is packing of the tower with objects which have a large surface area. As the liquid flows down over the packing it wets the surface to present a correspondingly large area to the ascending gas. This packing may be interlocked wooden slats, similar to the construction of a cooling tower, or it may be nothing more than coke or crushed rock insoluble in the absorbent. Crushed material is usually quite cheap but must be carefully sized to uniform dimensions, lest the pressure drop become intolerable for the gas system. Coke has a further slight disadvantage, in that its multitude of pores become filled with liquid which acts as a brake on attempts to change operating conditions to meet changes in the gas fed to the tower.

Several shaped packings have been developed to increase the area of contact, notably Raschig rings, Berl saddles, spiral rings, grids, and coarse glass fibers. Raschig rings (Fig. 2) are short pieces of thin-walled metal or ceramic tubing, with length equal to diameter. Berl saddles (Fig. 3) are saddle-shaped pieces, usually ceramic, so designed that the surface is not blocked from liquid or gas flow regardless of the position into which they fall. Both the rings and the saddles are piled helter-skelter into the tower, with no attempt at expensive manual positioning of each piece, and their shapes are such that the absorption coefficient and pressure drops are surprisingly reproducible for different random piles.

Spiral partition rings (Fig. 4) are manually positioned with the axis vertical, and usually with staggered positioning in successive layers. Grids are hollow square tiles, somewhat resembling construction blocks with multiple partitions to provide more surface. They must be manually positioned also. Glass fibers are inserted in bundles of vertical fibers, and require intermediate supports in taller towers to prevent packing down of the bundles. Crimped and twisted wire gauze and ribbed and perforated plates are other packings from the list available.

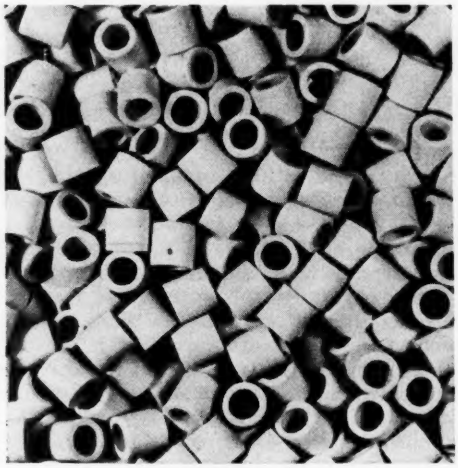


Fig. 2.
Porcelain Raschig rings. Courtesy, Lapp Insulator Co.

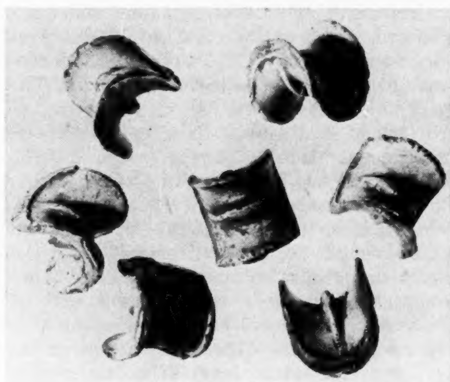


Fig. 3.
Porcelain Berl Saddles. From G. G. Brown and associates, "Unit Operations of Chemical Engineering," John Wiley and Sons, 1949

The fixed perforated plate and bubble-cap plate are more positive devices for insuring good contact between the gas and liquid phase. Fig. 5 shows a tower containing several such plates, each showing different bubble caps. Towers equipped with these plates have well-defined flow paths for each

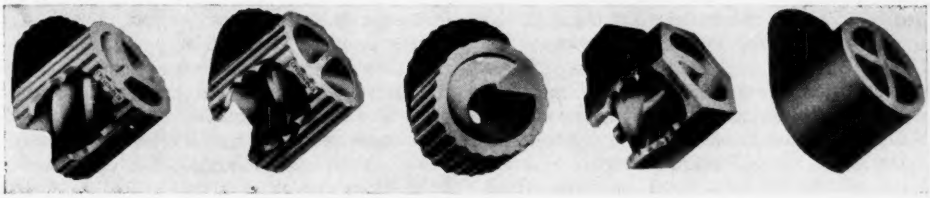


Fig. 4.
Typical spiral partition rings. Courtesy U. S. Stoneware Co.

phase, with the liquid always moving horizontally across each plate, over the control wire and down a pipe to the next plate, while the vapor bubbles up through the liquid crossing the plate. Such towers are used extensively in the distilling and petroleum industries for absorption and for fractionation and the literature on their design, operation, and characteristics is voluminous.

## Absorbents

THE ideal liquid to be used in any absorber is one which will remove the vapor satisfactorily, and which itself will release the vapor easily in a higher concentration

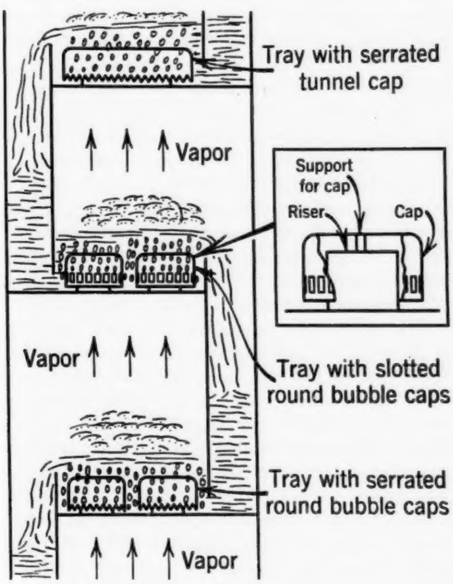



Fig. 5.
Section of tower equipped with bubble-cap plates. Each plate is drawn with different caps for illustrative purposes. From G. G. Brown and associates, "Unit Operations of Chemical Engineering," John Wiley and Sons, 1949

and can be recirculated for re-use. Water is satisfactory for many vapors, but some of the more troublesome vapors are not readily soluble in water and could not be sufficiently absorbed without large and expensive equipment. Other liquids which are more expensive in themselves may permit simpler and less costly equipment. For example, hydrogen sulfide may be absorbed in solutions of sodium carbonate, arsenious oxide and soda ash, diethanolamine, sodium phenolate, or tripotassium phosphate. Actually, the absorption in these liquids involves a chemical reaction in which the hydrogen sulfide is transformed into a more agreeable compound, but in all cases the addition of air, steam or heat reverses the reaction. The hydrogen sulfide is then liberated in a more concentrated form, which simplifies its disposal by conversion to sulfur or sulfuric acid or even by sale in the concentrated form as a by-product. The regenerated absorbent is returned to the absorber and used again and again.

An earlier paper in this symposium mentioned the transformation of sulfur dioxide into sulfuric acid. Absorption is occasionally a useful prelude to this process, as at Trail, British Columbia. The sulfur dioxide in roaster gases in dilute concentrations may be absorbed in ammonium sulfite solution and later released as 100-percent sulfur dioxide by treatment with concentrated sulfuric acid. The pure sulfur dioxide may be converted into sulfuric acid or into free sulfur by succeeding treatment.

Whatever the liquid absorbent, it is rarely economical or possible to throw it away. It must be stripped of the vapor in solution and returned to the absorption tower. Occasionally it is cleaned chemically, as mentioned above, but usually it is stripped by a reverse process to absorption. The rich solution is fed to the top of a regenerating tower (see Fig. 1) built like an absorber. A mixture of vaporized absorbent and un-

desirable vapor moves upward through the tower, freeing the undesirable vapor from the descending solution, and adding its absorbent to the descending liquid. The liquid reaching the bottom of the tower is partially vaporized by heat from steam coils, or by direct introduction of steam in some cases, producing the vapor mixture which rises through the tower. The unvaporized liquid, low in content of the undesirable vapor, is withdrawn from the regenerating tower, cooled, and returned to the top of the absorption tower. The gas leaving the top of the regenerating tower is rich in the undesirable vapor, and may be introduced back into normal plant streams, processed to make a by-product, or sold as a by-product.

### Adsorption

THE equilibrium relationship for adsorption may be expressed by the same general equation,

$$y = kx$$

in which y is the concentration of the vapor in the gas phase in equilibrium with the adsorbent, k is the equilibrium coefficient, and x is the "concentration" on the adsorbent surface. As in absorption, equilibrium represents a dynamic balance, with molecules of vapor leaving the adsorbent layer at the same rate as they enter it from the gas phase. The equilibrium coefficient is quite variable in adsorption, and is a function of many physical factors. Its variations are so erratic that the mechanism of adsorption, by which is meant the reasons for the attraction of molecules of certain vapors to the adsorbent surface and the ways in which they are held there, is not known to an extent satisfactory to all authorities.

The simplest theories of the mechanism hold that the vapor molecules are attracted by the "surface tension" of the solid molecules on the surface. The surface tension, which has never been measured satisfactorily, exists because the molecules of solid are held to one another by strong forces which are unsatisfied on the exposed side of the surface molecules. This theory can account for only one layer of vapor molecules, unless it is extended to the exposed surface of the first layer of vapor molecules, which in turn will have a surface tension, etc.

The most serious objections to this theory arise from unexplainable variations in the adsorption relations from one solid to another for the same vapor, and from one vapor to another for the same solid. A complicating factor is the lack of knowledge of the area of adsorption on any one solid. Data on preferential adsorption frequently show that some solids with surfaces known to be porous will adsorb more of a vapor with small molecules than of a chemically similar vapor with large molecules, but that surfaces of the same solid thought to be nonporous do not show the same relative adsorption. This leads to a theory that the pore openings, or many of them, may be so small as to filter out the larger molecules and to permit the small molecules to enter into the pores and be adsorbed. Obviously, pores of such size cannot be seen by any microscopic technique in use, thus the theory is unsubstantiated by visual observation and the surface area is unknown to that extent.

The most promising explanation of the mechanism is an extension of the "surface-tension" theory to a "condensation" theory. The vapor molecules on the surface have volume concentrations corresponding to those of the liquid phase, and upon adsorption release heat in quantities corresponding to the heat of condensation. The amount of vapor adsorbed increases almost proportionally to the condensing temperature of the vapor up to the operating temperature of the adsorber. Such data lead to the idea of condensation as the real mechanism, with the unsatisfied energy demands of the solid surface reducing the energy level of the vapor to that of its liquid phase. This theory also has its faults and its unexplained data, but in the gross form is the best simple explanation now available.

The lack of proved knowledge of the mechanism of adsorption leads to a wholly empirical approach to practical problems. Few authorities will extend their experience to a prediction regarding adsorption of an unfamiliar vapor, even on a familiar adsorbent. In fact, it is highly desirable that each proposed installation be checked experimentally before the design is fixed. This is especially true because of the tendency of some materials to "poison," or render non-adsorbing, a given adsorbent, even when the contaminants are present in traces only. Another factor not predictable in advance is the effect of mixed gases and vapors. Most commercial adsorbents will adsorb many different vapors, but simultane-

ous adsorption may cause mutual interference and wide deviation from the expected results as indicated by experiments with individual vapors. This may be preferential to such an extent that mixed materials passing through a relatively thick bed of adsorbent will displace one another until one vapor is concentrated near one end of the bed, another farther along, and perhaps another still farther along. This action is exploited commercially in the production of such things as vitamins, xanthophyll, and chlorophyll in relatively pure form. Such a process of fractional adsorption is called chromatography, from the color banding which occasionally occurs as a result.

When data are available to enable construction of an adsorption system, it is an attractive technique for removal of undesirable vapors. First, it reduces the vapors to lower concentrations than any other physical process. The equilibrium data show that relatively high concentrations on most adsorbents have low vapor pressures, and therefore the capacity for vapor removal is high.

Second, it is extremely rapid in action, with thin beds being sufficient for the lower concentrations of vapors. The adsorption is not delayed by counter-diffusion and diffusion of the vapor into the removing material, therefore it takes place almost instantaneously in most cases.

Third, it is reactivated easily and releases the vapors in high concentrations which are suitable for conversion or actual sale. Reactivation is usually only a heating or steaming process, with low-pressure steam being sufficient for both purposes.

Fourth, it can be made completely automatic for a reasonable cost.

## Adsorbents

ONE of four adsorbents usually is used in a system to remove vapors from gases. These are activated carbon, silica gel, activated alumina, and activated bauxite. Bauxite is an ore containing either the monohydrate or the trihydrate of alumina, $Al_2O_3$, and is thus cheaper than the other materials which are the products of special processing methods. It is activated by "burning" at temperatures up to 1600° F. Activated alumina is a purified trihydrate of alumina processed to make it into highly porous granules. It is activated by preheated gas or air being blown through it. Both materials are used in large quantities as desiccants, having a great affinity for water. They do adsorb other vapors to some extent, but have not attained appreciable usage in this capacity, therefore they are not of great interest in control of air pollution.

Silica gel is a hard glossy granular form of silica, $SiO_2$. It is made by reacting sodium silicate and hydrogel of about 10% silica and 90% water. The sodium sulfate is washed out carefully and the hydrogel dried to solid silica gel. Water may be adsorbed up to 40% of the weight of the silica gel, while other vapors are adsorbed to a lesser degree. For example, sulfur dioxide is adsorbed up to about 5%, decreasing with decreasing concentrations in the gas mixture and decreasing temperatures. Organic vapors are also adsorbed in similar quantities. Because of its high capacity for water, silica gel is used extensively for desiccation, but is being advanced by its manufacturers for removal of other vapors. As yet, its use of control of air pollution is slight, but growing.

Activated carbon is usually the charcoal of cellulosic material, with coconut shells being used extensively, fruit pits and nut shells to a lesser degree. Activation is performed by introduction of superheated steam during carbonization, after distillation of all other products. The adsorptive capacity varies considerably with the source of the cellulose, and even varies with the place of growth of the same species. Practically all vapors are adsorbed to some degree, but water is poorly adsorbed compared to organic vapors and to such air pollutants as sulfur dioxide and hydrogen sulfide. Consequently activated carbon is used extensively for solvent recovery and pollution control, but not at all for dehydration.

## Adsorbing Equipment

THE design of the equipment depends upon the amount and kind of gas to be handled, the concentration and nature of the vapor to be removed, and the method of regeneration to be used. Two basic kinds of operation are usual in pollution work, thin beds for dilute concentrations and thick beds for higher concentrations. The thick beds are installed in horizontal tanks or vertical towers with supports at intervals.

Usually the adsorbers are supplied in pairs, with one on stream while the other is being reactivated in place, using low-pressure steam. Thick beds are more common in solvent recovery than in pollution control.

For more dilute concentrations the carbon may be placed in trays in horizontal tanks, arranged so that the gas flows either upward or downward through a tray before it leaves the tank. Fig. 6 shows an arrangement which fits in the ventilating system, with the carbon placed between concentric cylindrical screens to hold the granules in the form of a hollow cylinder. These canisters are standard in size, and can be screwed like light bulbs into plates in the ventilating system. Such thin beds are usually reactivated in bulk in special equipment, by steam or simple raising of the temperature. Moisture remaining adsorbed after reactivation is displaced by the preferentially adsorbed vapor and discharges along with the exhaust gas. When the vapors are mixed and not disposable by incineration, regeneration may create a disposal problem equal to the original one. For example, a perfume manufacturer in New Jersey recently stated that his plant, in the center of a residential district, finally solved the problem by shipping the carbon back to the manufacturer for reactivation.

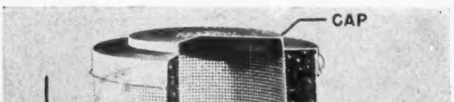



Fig. 6.
Hollow cylindrical canister for odor control by activated carbon. Courtesy, W. B. Connor Engineering Co.

The use of continuous adsorption systems, with the carbon granules flowing in a fluidized fashion down through a series of plates in a tower and the gas rising through the mass, is increasing rapidly for higher concentrations but is not yet in use for pollution control.

Adsorption releases heat in such quantity that some thick-bed installations must be cooled artificially to prevent release of the already adsorbed vapor or to keep the capacity of the unit at a high level. Water cooling is sufficient.

## Comparisons of Absorption and Adsorption

COMPARISON of absorption and adsorption as means of removing undesirable vapors from gases is not easy. Adsorption is excellent when large quantities of gas with very low concentrations of vapor are to be handled, and absorption is better when more concentrated vapors are used, since a continuous process is more adaptable to such a duty. Adsorption requires filters or other means of removing dust from the gas prior to entering the adsorber, but absorption requires follower devices to guard against entrainment of the liquid absorbent in the gas leaving. Adsorption reduces the vapor concentration to zero or to traces in many cases, while absorption has appreciably higher limits in most cases.

Both adsorption and absorption must be operated at low temperatures, preferably below 100°F. This means they are not applicable to stack gases because of the cooling load and loss of draft. For stack gases the dilution technique of tall stacks discharging hot gases at advantageous locations is apparently the best answer for vapors whose presence is unavoidable. Many vapors can be handled satisfactorily and dispersed sufficiently by incineration with a gain in draft because of the heating effect.

As always, control of air pollution must be developed by analysis of the pollutants and their source, followed by application of the best corrective techniques for each job.

## Discussion

### Air Pollution Institute, Ann Arbor, Michigan, February 8, 1950

MR. THOMAS: I would like to ask MR. GOSLINE something that isn't quite clear. Does application of the Bosanquet-Pearson and Sutton equations give the theoretical maximum concentration?

MR. GOSLINE: The Bosanquet-Pearson formula, and Sutton, as well, give the average concentration at a point during a long period of time, say more than an hour and I am sure there is difference of opinion about that. At any rate, you don't use the Bosanquet-Pearson and Sutton formulas on two- or three-minute concentrations. The concentration should be the average for, say, a period of an hour.

MR. NICHOLSON: I have a question I would like to direct to MR. GOSLINE. There is another problem that has not been touched on in connection with smoke and fly ash from large boiler installations. We have seen efficiency diagrams and various means and methods used to keep down air pollution and we have heard about electrostatic precipitation and how it can be effective if it isn't overloaded. We have several plants and there are numerous big industrial and utility plants that have these large pulverized fuel boilers. Their experience is similar except for about a half hour out of every eight hours when tubes are blown. Then the electronic precipitator gets overloaded and control of air pollution is lost. What is the solution, and what are the trends towards cutting down excessive fly ash and smoke during the blow down period?

MR. GOSLINE: Efficiency in operating a boiler makes it necesary to get the soot out now and then. Many plants do that at night regularly. Overloading an electrostatic precipitator will result in a very large carryover to the atmosphere when tubes are blown. In other words, the retention time in the collector goes down because the gas velocity increases owing to the increased volume during that time. With the cyclone collectors, the reverse is true. When you overload as you increase the velocity on the cyclone collector, you may take a power penalty, but you increase the collection efficiency. The question was asked yesterday: What is being done about rapping the wires of the electrostatic collectors? The recent research Cottrells have a continuous pneumatic rapping device. I observed them at the Rochester Gas and Electric installation and they work very well provided they are not pounded too hard. The idea is to rap just hard enough to cause the ash to trickle down along the wires into the hopper. If rapped too hard, the dust is shaken free from the wires and must be re-collected, which reduces efficiency. The difference between 10 pounds of air pressure and 30 pounds of air pressure on the graph is the difference between 97% collection with the 10-pound pressure and an 88% collection with 30-pound air pressure.

MR. NICHOLSON: You spoke of these automatic rapping devices on the collectors. I understand there is coming into use what is termed a power puff continuous automatic tube blowing. I wonder if that isn't a trend in the right direction rather than having one particular period for blowing tubes. If tube cleaning could be stretched out over the whole period it would be a great improvement. We would like to see the manufacturers develop such ideas, as the boilers are made larger in consideration of the people who clean them.

MR. GILL: I would like to ask Mr. Gosline how he distinguishes between the particles he collects.

MR. GOSLINE: On the night I described, the major source of pollution in the air was known. When we saw the trail of ash coming toward us and could see it going past us, and around us, and over us, we got our samples. There is no doubt that they were from that stack. That's the advantage of mobile sampling. If there is a straight wind from the stack and you can see the plume and obtain samples it is reasonably certain they are on. If you set something out for a few days or weeks, results are confused by wind direction, weather and other things. We have found that, because answers are wanted immediately, mobile sampling works best from that standpoint, but it may not be the right answer for fundamental research projects or problems requiring periodic sampling.

MR. SHAW: I would like to direct a question to Dr. Bishop. I am wondering if you use coke oven gas in your work and whether you had had any tests for hydrogen sulphide?

DR. BISHOP: We do make coke oven gas in Pittsburgh and it contains some $H_2S$.

MR. SHAW: What sort of percentage or concentration?

DR. BISHOP: It depends on the coal used. It varies between 200 grains per 100 cu. ft. and 600 or 700, depending on the coal used. You cannot remove the $H_2S$ by some processes because of the cyanide present, but you can use sodium carbonate. I might add that in the steel industry we have dust particles so small

we need an electron microscope to find them.

DR. MCCABE: I am sure I express the feeling of all of us when I say that we are indebted to the University of Michigan School of Public Health for offering this course in atmospheric pollution. We are indebted to the speakers who have come here and given their time. It is a tremendous job to organizing a conference of this sort. We are grateful to DEAN VAUGHAN and to MR. MILLER for the work they have done, as well as to those who have been on the local Planning Committee.

I was talking last night with some of those in attendance who feel that this conference has been one of the prime opportunities. In the evening we have gathered informally to discuss some of the problems beyond the time limits of the scheduled program. There is evidence that we are gaining a better understanding of the air pollution problem. An impressive amount of knowledge is becoming available that is applicable to these problems. Many technical conferences on the subject have been held in the past year. This course is evidence that the information and its presentation are becoming better and more widely applicable.

It is unfortunate, I think, that there is much emotion attached to this problem at this time, but there are reasons for that, of course. However, progress is being made; much of the corrective action that must be taken by industry is expensive, it requires planning and construction and it does require time. But we are making headway. I would like to have you join with me in expressing our appreciation to the School of Public Health for offering this course.